FINAL REPORT

Natural Pressure-Driven Passive Bioventing

Naval Facilities Engineering Service Center

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ABBREVIATIONS AND ACRONYMS

AFB	Air Force Base
AFBCA	Air Force Base Conversion Agency
AFCEE	Air Force Center for Environmental Excellence
ARTT	Alternative Restoration Technology Team
AST	aboveground storage tank
bgs	below ground surface
BOS	buried oxygen sensor
BVCE	Bioventing Cost Estimator
cf	cubic feet
cfd	cubic feet per day
cfm	cubic feet per minute
CPT	cone-penetrometer test
DoD	Department of Defense
DOE	Department of Energy
DTSC	State of California Department of Toxic Substances Control
ESOH	Environmental Safety and Occupational Health
°F	Fahrenheit
ft	feet
ft^2	square feet
“H_2O	inches of water
HSA	hollow-stem augering
ID	inside diameter
IDW	Investigation Derived Waste
IRP	Installation Restoration Program
ISR	*in situ* respiration
mg/kg	milligrams per kilogram
MGACC	Marine Corps Air Ground Combat Center
MW	monitoring well
NAPL	Nonaqueous phase liquid
NFESC	Naval Facilities Engineering Service Center
O&M	Operations and Maintenance
O_2	oxygen
ORD	Office of Research and Development
ORP	Oxidation Reduction Potential
PFFA	Petroleum, Oils, and Lubricants (POL) Fuel Farm Area
POL	Petroleum, Oils, and Lubricants
ppmv	parts per million by volume
PVC	polyvinyl chloride
RAB	residential advisory board
R_i	radius of influence
RPM	Remedial Project Manager

ABBREVIATIONS AND ACRONYMS (continued)

RWQCB	State of California Regional Water Quality Control Board
SAP	Sampling and Analysis Plan
SIC	standard industrial classification
TDP	Technology Demonstration Plan
TKN	total Kjeldahl nitrogen
TPH-g	total petroleum hydrocarbons as gasoline
TPH-Jet A	TPH as jet propulsion fuel A
TPH-JP4	TPH as jet propulsion fuel #4
TVH	total volatile hydrocarbons
USEPA	United States Environmental Protection Agency
UST	underground storage tank
VMP	vapor monitoring point
VW	vent well
WBS	work breakdown structure

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1. Introduction

1.1 Background Information

The environmental problem being addressed by this technology demonstration of passive bioventing is contaminated vadose-zone soils. This technology addresses contaminants that are aerobically biodegradable, such as petroleum-hydrocarbons and many lesser-chlorinated hydrocarbons. Natural pressure-driven passive bioventing is not a new technology for addressing this environmental problem, but rather a new approach to conventional bioventing. Conventional bioventing is a proven, cost-effective remedial technology which has been applied at numerous Department of Defense (DoD) installations in the United States and worldwide.

Conventional bioventing requires at least one blower to either inject or extract air. However, it has been observed at several sites that natural movement of gases into and out of the vadose zone due to barometric pressure fluctuations can also provide soil aeration for aerobic biodegradation. To date, field demonstrations of passive bioventing techniques have been very limited in number and scope and thus this approach is not yet considered validated or definitively demonstrated.

The benefits of a passive approach are that the system would have a significantly simpler design and could be used at remote sites where power is either unavailable or cost-prohibitive to install. Alternatively, passive approaches could be used as a long-term remedial measure after more intensive, short-term remedial measures. Compared to conventional bioventing systems, passive bioventing systems would have lower power consumption, reduced operations and maintenance (O&M) requirements, less facility disruption, and increased reliability.

1.2 Official DoD Requirement Statements

This technology demonstration addressed the following DoD requirements:

- Navy requirement number 1.I.1.m - Improved Remediation of Soils Contaminated with Non-Chlorinated Hydrocarbons

- Air Force requirement ESOH (Environmental Safety and Occupational Health) Need #243 - Site Remediation, Hazardous Waste Treatment Technologies for Installation Restoration Program (IRP) Site Remediation of Hydrocarbon Compounds in Soil

1.2.1 How Requirements Were Addressed. These requirements were addressed through the field demonstration of passive bioventing as a potential cost-effective improvement to conventional bioventing. The demonstration was conducted at a site with petroleum-hydrocarbon contamination in soils, where conventional bioventing tests also were being conducted. Technical effectiveness was evaluated through real-time monitoring and a series of controlled tests. Oxygen increases in soil vapor was used as an indicator of treatment effectiveness for bioremediation of the site contaminants. Cost information was gathered during the field demonstration to compare passive bioventing cost performance against conventional bioventing costs and other competing technologies.

1.3 Objectives of the Demonstration

The primary objective of this demonstration was to determine the applicability of passive bioventing techniques to a wider variety of site conditions than previously studied.

The specific objectives of this demonstration were:

1) Evaluate a passive approach to bioventing using air flow driven by changes in barometric pressure (no electricity or blower needed) under different site conditions than studied to date;

2) Measure achievable air flow rates, radii of influence, and treatment areas under different system configurations;

3) Compare the remedial effectiveness and cost-effectiveness of passive bioventing to conventional bioventing; and,

4) Gather data in support of a design document to support technology implementation at future sites.

The scope of this demonstration needed to satisfy the above objectives was:

1) Conduct a field demonstration of passive bioventing at a site with characteristics conducive to passive bioventing, but which had not been studied to date (*i.e.,* lithologically stratified with shallow groundwater);

2) Collect data to aid in the evaluation of how site variables (*e.g.,* barometric pressure, soil moisture, stratigraphy, and well configuration and depth) affect air flow rates, oxygen concentrations in the subsurface, radius of influence, and treatment area;

3) Develop a technical report which contains the results from sampling and testing activities and comparative technical performance and cost performance analyses between conventional bioventing and passive bioventing; and,

4) Develop a user data package that incorporates all of the above analyses and reports in order to transfer the technology.

This technical report and the previously-submitted user data package satisfy the objectives and the scope items listed above.

The location for the field demonstration detailed in this report was a site at Castle Airport (formerly Castle Air Force Base [AFB]), located in Merced County, California, approximately 5 miles northwest of the city of Merced (Figure 1). The specific site location within Castle Airport where the demonstration was conducted is the Petroleum, Oils, and Lubricants (POL) Fuel Farm Area (PFFA). The PFFA is located in the southern portion of the Main Base Sector and was the bulk fuel storage and distribution facility (Figure 2).

1.4 Regulatory Issues

The regulations which apply to the cleanup of contaminated, vadose-zone soils are generally driven by either promulgated concentration standards, which typically vary from state to state and even locally within states, or are driven by human health risk-based remediation goals for soil or groundwater. In addition, other types of laws, such as state non-degradation policies for groundwater, may drive development of remediation goals.

Regardless of the methods used in the determination of remedial goals, bioventing has been successfully used to meet these remedial goals and achieve site closure as defined by regulatory agencies. As of October 1994, regulatory acceptance of bioventing had been obtained in all 10 USEPA regions and in 30 states (USEPA, 1999). Passive approaches to bioventing have the potential to be equally accepted.

The effectiveness of the technology can be demonstrated to the regulatory agencies through periodic monitoring. This monitoring would include periodic respiration testing; periodic soil vapor sampling to determine oxygen, carbon dioxide, and contaminant concentrations; and, when monitoring data indicates it is appropriate, confirmatory soil sampling to achieve site closure. The use of the passive valve (Section 2.1.3) to minimize exhalation of contaminated soil vapor would help address potential atmospheric emissions and minimize the need for air emissions permits.

Other regulatory issues such as local regulatory agency concurrence with work plans, digging permits, well installation permits, and disposal of investigation-derived waste (IDW) also typically apply to this remedial technology.

1.5 Previous Testing of the Technology

Passive bioventing using barometric changes has been engineered at two DoD sites and one Department of Energy (DOE) site in the United States. At the Twentynine Palms Marine Corps

FIGURE 1

FACILITY LOCATION MAP

Castle Airport, California

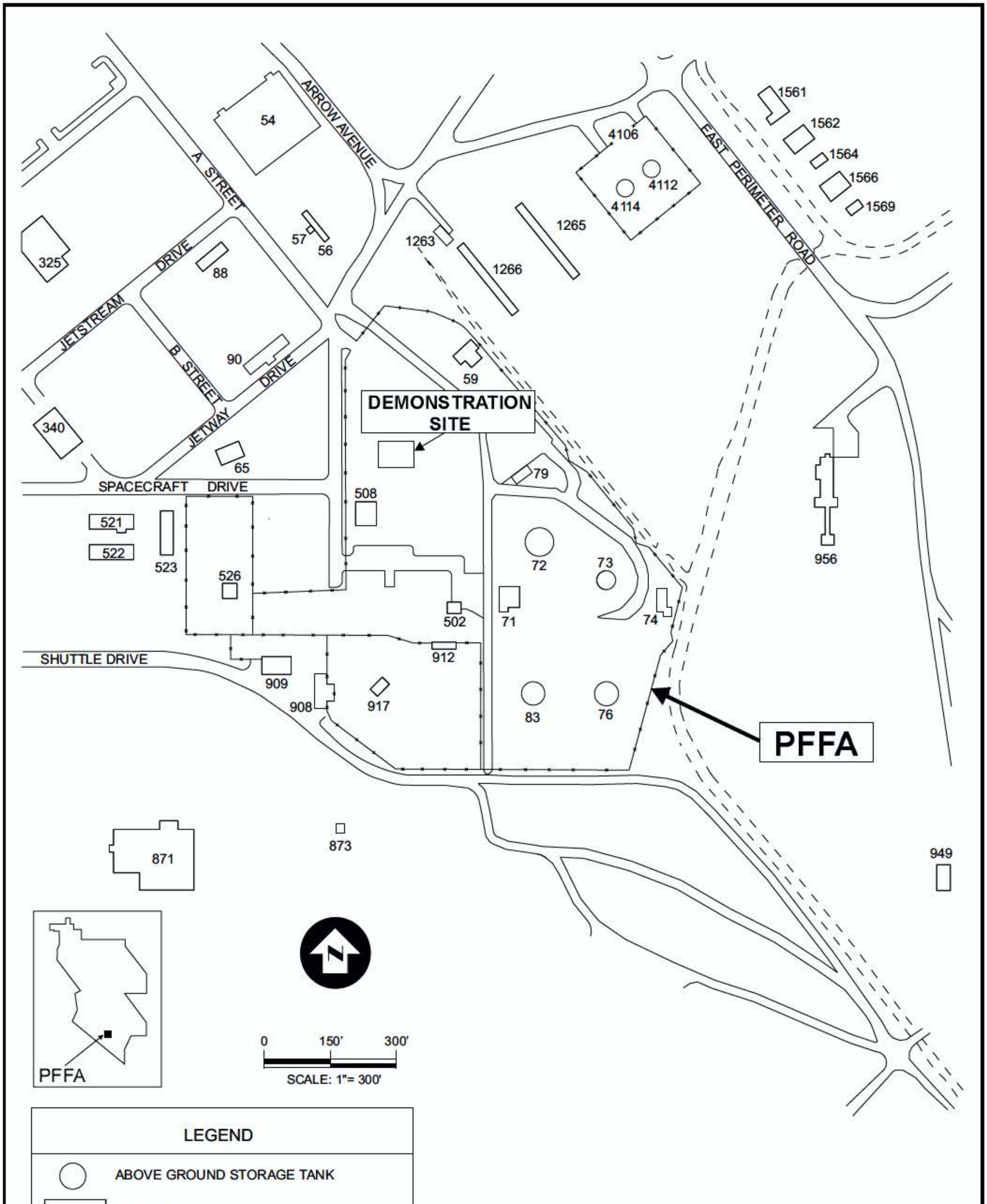

FIGURE 2

SITE LOCATION MAP

PFFA
Castle Airport, California

Air Ground Combat Center (MCAGCC) in southern California, natural daily barometric pressure changes could induce air flows of up to 15 cubic feet per minute (cfm) into vadose zone wells for short periods of time (Foor *et al.*, 1995; Zimmerman *et al.*, 1997). The depth to groundwater at Twentynine Palms is approximately 200 feet below ground surface (bgs) and the lithology is primarily medium- to coarse-grained sands. Through the use of a one-way check valve (also called a passive valve), oxygen concentrations were increased in the vadose zone 9 feet from the injection well. The radius of influence was not directly measured, but was inferred from pressure measurements to be 20 feet.

At Hill AFB in Utah, during a one week test air flow rates of up to 5 cfm were obtained. The depth to water at the Hill site is approximately 100 feet bgs (Battelle, 1995). At the Savannah River Site in South Carolina, air flow rates from an extraction well were as high as 6 cfm at a site with a depth to groundwater of approximately 120 feet bgs (Rossabi *et al.*, 1993; Rossabi *et al.*, 1998).

Although theoretically passive bioventing should work under certain conditions with shallow groundwater and stratified soils, it had never been demonstrated prior to the demonstration at Castle Airport described in this report. The DoD most likely has more sites fitting this description than deep groundwater sites.

2. Technology Description

2.1 Description

2.1.1 Introduction. Bioventing is an effective, proven, cost-effective, *in situ* biological treatment technology for unsaturated soils containing contaminants amenable to aerobic biodegradation. Bioventing technology is used to remove contaminants from vadose-zone soils by providing oxygen to natural, aerobic microorganisms which break down these contaminants.

Bioventing has a widespread potential application because soil microorganisms are capable of degrading most petroleum products (including gasoline, jet-propulsion fuel, diesel fuel, and heating oils) under aerobic conditions. Bioventing technology has a particular advantage for soils contaminated with less volatile fuels since technologies that depend on volatilization, such as vapor extraction, are not very effective with these compounds.

Conventional bioventing requires at least one blower to either inject or extract air. Oxygen in ambient air is supplied to naturally occurring microorganisms which aerobically degrade the contaminants. A small, regenerative electric blower is usually used to inject air into vent wells (VWs) installed above the water table in contaminated soil. Relatively low air flow rates (on the order of 15 to 30 cfm per well [20,000 to 40,000 cubic feet per day (cfd) per well]) and low injection pressures (on the order of 10 to 30 inches of water) are used to minimize volatile loss

while maximizing biodegradation. Conventional bioventing has been successfully demonstrated at DoD installaitons and other facilities (Miller *et al.*, 1993; Leeson and Hinchee, 1997). Conventional bioventing is included in the list of treatment technology profiles in the *Remediation Technologies Screening Matrix and Technology Guide* (USEPA, 1999).

2.1.2 Passive Approaches to Bioventing. Passive bioventing differs from conventional bioventing in the way oxygen is delivered to the subsurface. Instead of electric blowers, passive bioventing relies on natural air exchange.

Previous field tests have shown that daily changes in barometric pressure cause open vadose wells to inhale and exhale air (sometimes termed "barometric pumping" or "breathing") (Pirkle *et al.*, 1992; Rossabi *et al.*, 1993, Foor *et al.*, 1995; Zimmerman *et al.*, 1997). This phenomenon is illustrated on Figure 3. During times of increasing barometric pressure, a negative pressure gradient is potentially developed between the atmosphere and the subsurface, which is measurable as a vacuum at subsurface monitoring points. Air flow can occur into the subsurface if vent wells or monitoring wells are installed and appropriately screened at depths where significant gradients are developed. The reverse effect occurs during times of decreasing barometric pressure (*i.e.,* positive pressure gradients are developed and air flows out of the well).

The magnitude of the pressure gradient (and also the magnitude of the air flow rate) is primarily a function of the rate of barometric pressure change, depth, soil air permeability, and soil porosity (Zimmerman *et al.*, 1997). The relationship between the pressure gradient and these variables manifests itself as a lag time between the changes in barometric pressure and the subsurface pressure, as well as a dampening of the magnitude of the barometric pressure change in the subsurface.

Barometric pressure varies daily with air temperature fluctuations, with pressures usually lowest in the afternoon and highest in the early morning. Weather front (long-term) barometric pressure changes can also be significant. Typically barometric pressure varies diurnally on the order of approximately 0.2 inches Hg from day to night. The passage of periodic weather fronts can cause an even greater change in barometric pressure. However, a significant change in barometric pressure alone is not a sufficient guarantee that pressure gradients will actually be developed or can be engineered in the subsurface to create the air flow required. As indicated above and further presented in Section 5, site lithology and soil characteristics are just as important.

2.1.3 Passive Bioventing Design. Design of a passive bioventing system is almost identical to the design of a conventional bioventing system, except that an electric blower is not required and one-way passive air flow valves are installed at the VWs (Figure 4). Natural pressure gradients are used to replace the blower and the passive valves are used to enhance the treatment radius. In engineering or designing a passive bioventing system with vertical wells, the driving force for producing the required subsurface air exchange (or airflow) is provided by the pressure gradient between the atmosphere and the subsurface (Figure 3). Using the passive valve, air can enter the VW only when inside well pressure is lower than atmospheric (due to

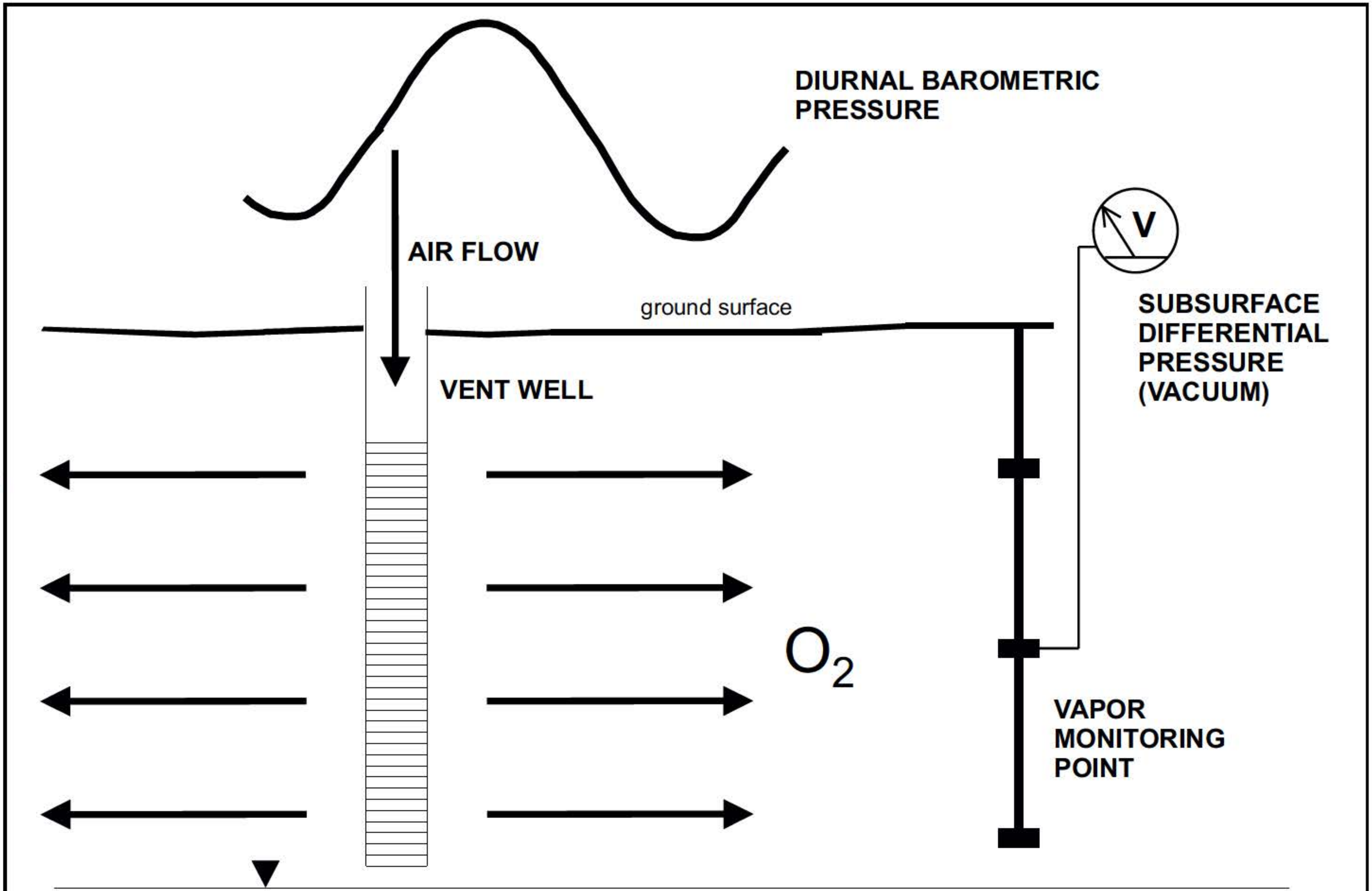

FIGURE 3

PASSIVE BIOVENTING PROCESS

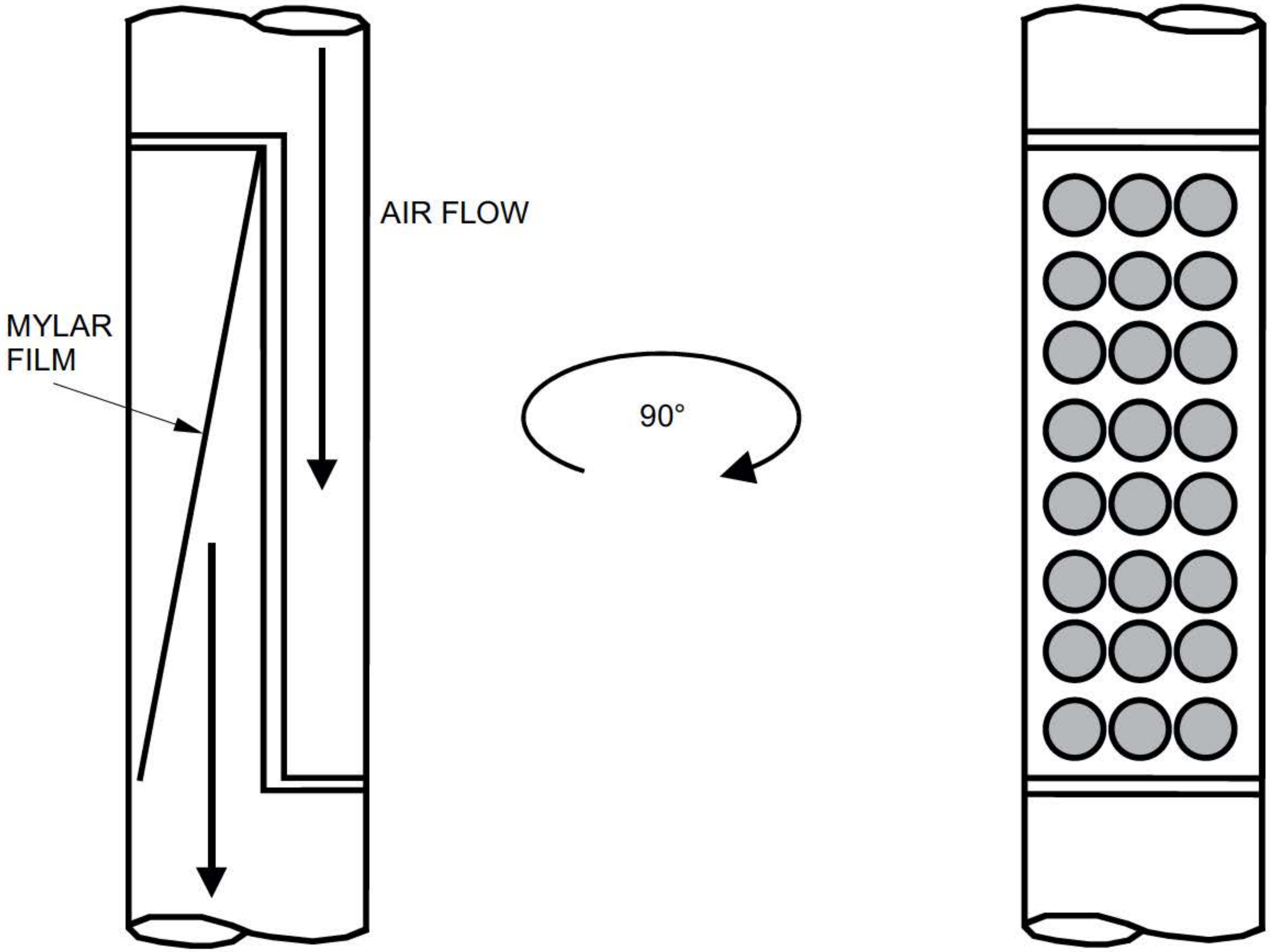

FIGURE 4

ONE-WAY, PASSIVE VALVE

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barometric changes). When the reverse gradient occurs, the valve closes to prevent the exhalation of previously injected air. Because horizontal permeability is typically much greater than vertical permeability, through successive air injection events the treatment area expands as previously injected air moves outward from the VW.

In addition to the VWs used for air injection or extraction, soil vapor monitoring points (VMPs) are used to monitor system performance and are an important part of bioventing system design. The VMPs are spaced radially around the VWs at distances expected to be under the influence of the VWs (Figure 5). Oxygen, carbon dioxide, and contaminant concentration measurements are taken from vapor samples collected from the VMPs in order to determine the radius of influence and treatment area.

Potential enhancement to system designs include using a tandem series of multiple VWs and one-way valves in different configurations, where some VWs are used for air injection and others are used for air extraction. In such a tandem arrangement, air flow could be directed to specific areas or underneath buildings.

2.1.4 Key Design Criteria. The key design criteria for passive bioventing systems is the required spacing for the VWs, based on the expected radius of influence and the air flow rate into the VW. As the expected radius of influence and air flow rate decrease, a larger number of closely-spaced VWs is required to treat an area of contaminated soil. Eventually, the cost savings realized from not installing and operating a blower would be offset by the substantial increases in drilling and VW installation costs if the radius of influence is small. Additional details on the site characteristics which affect these key design criteria are provided in Section 2.3.

2.1.5 Performance Objectives. The performance objectives are designed to establish under what circumstances passive bioventing can be practical and cost effective. The two primary performance objectives for this demonstration project were:

1. Achieve an adequate radius of influence to be economically viable; and,
2. Achieve air flow rates sufficient to meet the biological demand.

Because the radius of influence and oxygen demand of microorganisms will be site-specific, the success of the technology will necessarily be based on the ability to achieve an economical radius of influence from VWs and induce air flow needed to meet site-specific oxygen demands rather than on presumptive numerical values. The treatment area and air flow requirements must be met economically, without an excessive number of VWs required compared to a conventional bioventing approach. Additional details on the performance objectives are provided in Section 4.1.

2.2 Strengths, Advantages, and Weaknesses

2.2.1 Strengths, Advantages, and Weaknesses of Conventional Bioventing Over Other Technologies. The major advantage of conventional bioventing over other remediation

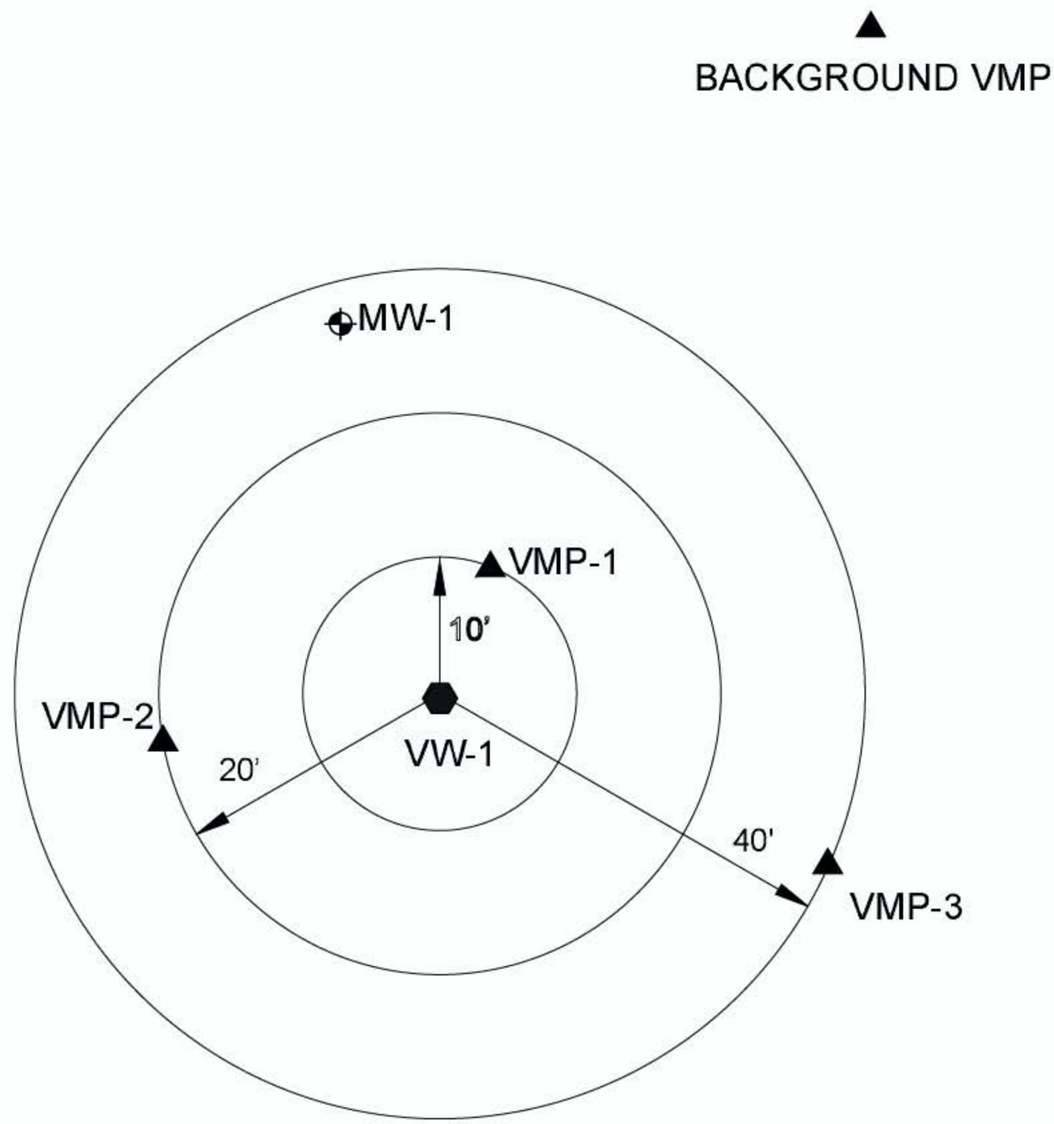

FIGURE 5

PLAN VIEW OF BIOVENTING WELL PLACEMENT (TYPICAL)

technologies is that it is a proven, cost-effective technology that promotes *in situ* biodegradation of petroleum hydrocarbons in soil under a wide range of site conditions.

The major weaknesses include that it can only be applied to vadose zone contamination amenable to aerobic biodegradation (*e.g.,* petroleum hydrocarbons and chlorobenzenes), its effectiveness is limited at sites with soils with low air permeability, and very low soil moisture can limit biodegradation (USEPA, 1999). The presence of preferential pathways, caused by stratification or other primary or second features in the subsurface can also cause limitations/performance problems. These problems include:

- Vertical preferential pathways, such as abrupt changes in lithology, deep root zones, or anthropomorphic features, could cause air flow to short circuit to the ground surface.

- Horizontal preferential pathways, such as higher permeability horizons, bedding planes, and anthropomorphic features, may inhibit remediation if they act to direct air flow away from or restrict air flow to contaminated zones.

The same weaknesses listed above for conventional bioventing also apply to passive bioventing.

2.2.2 Advantages of Passive Bioventing Over Conventional Bioventing. The primary advantage of passive bioventing over conventional bioventing or other remediation systems is elimination of the need for a blower and electrical power. At many facilities power is either unavailable or would be very expensive to obtain. Even at facilities where access to power is available, often contaminated sites are far away from power access points and operations and maintenance (O&M) costs for the system are largely due to blower and power requirements.

If appropriately constructed (*i.e.,* an adequate screened interval intersects the contaminated vadose zone soils), many existing monitoring wells (MWs) could be converted to passive bioventing wells by simply converting their existing well caps with downhole passive valves. Although this application of the technology may not work on all wells and not every contaminated site has a network of wells, given the very low cost, even a success rate of 1 in 5 or 10 sites would result in very low cost remediation.

2.2.3 Weaknesses of Passive Bioventing Compared to Conventional Bioventing. The primary weakness of the passive technology is that adequate subsurface pressure differentials must take place in order for the required air flow rates and radii of influence to be achieved. Sites where these conditions would not be expected to exist include sites without significant barometric pressure changes, sites which have soils with very low air permeability (*i.e.,* soils composed almost entirely of silt and clay), and sites with shallow groundwater and very limited lithologic stratification. At these sites, conventional bioventing or other remedial technologies would need to be applied.

The primary reason that passive bioventing is probably not applicable to sites with homogeneously tight soils is that the barometric changes produce a lower pressure head

compared to the blowers used in conventional bioventing. The lower pressure head would be unlikely to result in significant air flow with distance at these sites. However, at heterogeneous sites where there is a combination of both very permeable and less permeable zones (*e.g.,* interbedded sands and clays), both passive and conventional bioventing systems would produce air flow primarily in the more permeable zones. Both approaches would rely on diffusional mechanisms for oxygen transport from more permeable to less permeable zones, rather than on advection or head differences. The lower pressure head itself would not inherently lead to lower contaminant destruction rates since diffusional mechanisms are the primary oxygen transport mechanism into less permeable zones with both systems.

Because the radius of influence and air flow rates for a passive system are likely to be lower than those for a conventional bioventing system, more VWs will likely be required at most sites compared to a conventional bioventing system to achieve similar remediation times. However, if the system is designed to deliver an air flow rate that is able to meet microorganism oxygen demand, remediation times would not significantly increase with a passive bioventing system compared to a conventional bioventing system.

As discussed in Section 2.3, it also may not be necessary to meet the maximum microbial oxygen demand. As areas near the VW are remediated and the oxygen demand is satisfied, the radius of influence should expand. While this expansion of the radius of influence may come at the cost of longer remediation times, the time/cost tradeoff may be acceptable at some sites.

2.3 Factors Influencing Cost and Performance

As discussed in Section 2.1.4, the key design criteria for passive bioventing systems is the required spacing for the VWs, based on the expected radius of influence and the air flow rate from the VW. As the expected radius of influence and air flow rate decrease, a larger number of closely-spaced VWs is required to treat an area of contaminated soil. Eventually, the cost savings realized from not installing and operating a blower would be offset by the substantial increases in drilling and VW installation costs if the radius of influence is small.

The expected radius of influence and air flow rate are primarily a function of the following site characteristics:

- magnitude of barometric pressure change;
- frequency of barometric pressure change;
- air permeability of the soil (a function of soil type, soil porosity, soil moisture); and,
- oxygen-utilization rate of microorganisms (*in situ* respiration rate).

The presence of nonaqueous phase liquids may create vapor migration hazards and decrease the air permeability of the soil. Other, less significant, factors which can affect biological respiration rates and, therefore, performance include:

- soil temperature;
- natural organic carbon content;
- soil pH; and,
- nutrient levels.

The parameters listed above are identical to those listed for conventional bioventing in the *Guide to Documenting Cost and Performance for Remediation Projects* (USEPA, 1995).

The required air flow at a site should be compared to the demand of the microorganisms to determine feasibility. A method for estimating the required air flow rate to meet the maximum demand of the microorganisms is given below (USEPA ORD, 1995):

$$Q = \frac{k_o \bullet V \bullet \theta_a}{(C_{max} - C_{min})} \qquad (1)$$

where:

Q	=	volumetric air flow rate [cubic feet per day (cfd)]
k_o	=	oxygen-utilization rate (*in situ* respiration rate) [%/day]
V	=	volume of contaminated soil [cubic feet]
θ_a	=	air-filled porosity [volume air/volume soil]
C_{max}	=	oxygen concentration of background/injected air [%] (typically 20.9%)
C_{min}	=	minimum oxygen concentration for aerobic conditions [%] (typically 5.0%)

For example, assuming a typical oxygen-utilization rate of 0.2% per hour (typical of most petroleum-contaminated soils), a contaminated vadose zone thickness of 50 feet, an air-filled porosity of 0.25 (θ_a ranges from 0.1 to 0.4 at most sites), and a radius of influence from the VW of 10 feet (the minimum radius measured at the Twentynine Palms site), Equation (1) gives an air flow requirement of approximately 1,200 cubic feet per day (cfd). Equation (1) is particularly sensitive to the radius of influence (with a slightly larger radius of influence of 15 feet, the air flow demand would be 2,700 cfd). Air flow rates at both the Hill AFB and Twentynine Palms sites were on the order of 3,000 to 5,000 cfd, indicating the feasibility of using passive bioventing to meet microorganism demand.

It may not be necessary to meet the maximum microbial oxygen demand at a site. It is expected that the radius of influence from a passive bioventing system would approach that of a conventional bioventing system over a relatively long time period. Although initially the radius of oxygen influence will be limited by the microbial demand near the VW, as areas near the VW are remediated and the oxygen demand is satisfied, the radius of influence should expand. While this expansion of the radius of influence may come at the cost of longer remediation times, the time/cost tradeoff may be acceptable at some sites.

The technique used to determine the radius of influence in conventional bioventing design protocols (see Section 4.3) is a pressure differential threshold of 0.10 "H_2O because it is conservative and, with a conventional bioventing pilot test, is easy to measure. The protocols also emphasize the use of air flow rates and biodegradation rates for a design radius of influence and indicate that sufficient air flow may occur with distance in higher permeability soils at

pressure differentials that cannot be measured. Because the passive bioventing technology is most applicable at sites with higher permeability soils, achieving sufficient air flow and measurable oxygen increases with distance is likely to be a better approach than using pressure differential thresholds.

Air-filled porosity can be highly variable and difficult to measure accurately. It is usually estimated from both measured soil moisture content and an estimate of the soil's total porosity from observed lithology; therefore, it is very sensitive to both of these parameters (USEPA ORD, 1995). Air-filled porosity can significantly affect the biodegradation rate and the predicted radius of influence because it is used to determine the volume of air available for replacement in the subsurface. Lower air-filled porosities lead to lower biodegradation rates (because less oxygen is delivered to a unit soil volume). Somewhat counter-intuitively, lower air-filled porosity leads to a larger radius of influence because for a unit volume of air flow, more soil volume is filled. Of course, it would expected that with very high moisture contents air flow itself might be reduced; therefore, the radius of influence might actually remain the same or even decrease. There is nothing inherently different about a passive system that makes it any more or less sensitive to air-filled porosity than a conventional bioventing system.

3. Site/Facility Description

3.1 Background

Castle Airport (formerly Castle AFB) is located in Merced County, California, approximately 5 miles northwest of the city of Merced (Figure 1). It occupies approximately 3,000 acres of land and is comprised of runway and airfield operations, industrial areas, and several non-contiguous parcels of land located near the former base. Castle AFB was selected for closure under the Defense Base Closure and Realignment Act of 1990 and was officially closed in September of 1995. Environmental investigations, underground storage tank (UST) removals, and soil and groundwater cleanup operations are ongoing. Some parts of the former base have been leased to public and private entities.

The Petroleum, Oils, and Lubricants (POL) Fuel Farm Area (PFFA), built in the 1940's, is located in the southern portion of the Main Base Sector and was the bulk fuel storage and distribution facility (Figure 2). Approximately 18 USTs were formerly located and four above-ground storage tanks (ASTs) (3 million gallon total capacity) are currently located at the site. Extensive remedial investigations identified soil and groundwater contamination, primarily petroleum hydrocarbons, as a result of surface spills, leaking underground storage tanks, and fuel distribution lines. Most of the site is paved with asphalt or concrete or covered with gravel.

Based on the information available, the standard industrial classification (SIC) code most applicable to the site is 4581 (Transportation by Air — Airports, Flying Fields, and Airport Terminal Services) and the waste management practice that contributed to the site contamination is Petroleum, Oil, and Lubricant lines and underground storage tanks.

General selection criteria for passive bioventing sites were detailed in Section 3.1 of the Technology Demonstration Plan (TDP) (NFESC, 1997). A comparison of the criteria and the characteristics of the PFFA site at Castle Airport is summarized in Table 1. Detailed data are provided in the Technology Demonstration Plan, Site-Specific Addendum (NFESC, 1998).

Table 1
Selection Criteria

Criteria	PFFA Site Characteristic
Biodegradable contaminants	Contaminant concentrations in soil as high as 28,000 mg/kg TPH and 279 mg/kg BTEX
Soils are oxygen-deficient	Soil vapor oxygen concentrations were less than 1% in contaminated areas
Average diurnal barometric pressure changes greater than approx. 0.1 in. Hg	Diurnal barometric pressure changes measured at approx. 0.1 in Hg during short-term testing
Conventional bioventing is planned for the site (to provide leveraged data and facilitate cost comparison)	Conventional bioventing was selected for the PFFA in the feasibility study and was planned as a remedial action
For shallow groundwater sites, stratified soils with a relatively high horizontal air permeability relative to vertical air permeability	Groundwater is at approximately 60 feet bgs and soils at the site are highly stratified (see Section 3.2.2)

3.2 Site/Facility Characteristics

3.2.1 Climate. The climate of the Merced area in central California, where Castle Airport is located, is semiarid, Mediterranean type and characterized by wet winters and long, dry summers with maximum temperatures often exceeding 100 degrees Fahrenheit (°F). Winters are very cool with high humidity. The mean annual temperature at Castle Airport is 62 °F; the mean monthly temperatures range from 45°F in February to 79°F in July. During the summer, the clear, dry air allows rapid radiation, leading to large differences between day and night temperatures (frequently 40°F or more).

The mean annual precipitation is 12 inches. Approximately 85 percent of the precipitation falls between November and April. The average monthly relative humidity ranges from a high of approximately 75 percent during January to a low of approximately 30 percent in July.

Winds from the northwest prevail throughout most the year. Although the strongest winds occur between January and March, daily peak wind speeds are typically between 10 and 20 knots throughout most of the year. Winter precipitation events are usually preceded by winds from the southeast.

3.2.2 Geology and Hydrogeology. The shallow subsurface stratigraphy at Castle Airport is characterized by Holocene to Pleistocene alluvial deposits consisting of interbedded sequences of sands, silts, and gravels. These deposits include the Riverbank and Modesto formations. Generally, the upper 20 feet of these deposits consist of eolian and Holocene flood plain sediments, while the deeper deposits consist of sequences of silts, sands, and gravels that increase in coarseness with depth. Hardpan composed of iron- and silica-cemented sands and silts is often encountered between approximately 2.5 and 15 feet below ground surface (bgs). Currently, shallow groundwater is generally encountered at approximately 50 to 70 feet bgs, although historically groundwater was as shallow as approximately 10 feet bgs in some areas. Groundwater pumping is extensive in the areas surrounding the former base.

A plan view of the demonstration area is shown on Figure 6 and a generalized cross-section through the demonstration area is shown on Figure 7. The subsurface in the upper 20 feet is comprised predominantly of silty sand, overlying a laterally continuous silt layer between approximately 20 and 25 feet bgs. Between 30 and 35 feet bgs, sand with little to no fines predominates. This sand is underlain by another continuous clay/silt layer approximately 5 to 10 feet in thickness. Below this second clay/silt layer, sand extends to the groundwater table. Well construction details and boring logs for VWs and VMPs in the demonstration area are provided in Appendix C.

3.2.3 Nature and Extent of Contamination. Extensive previous remedial investigations have identified soil and groundwater contamination at the PFFA (NFESC, 1998; Jacobs, 1995). Nonaqueous phase liquids (NAPLs) have not been found at the site. Soil and soil vapor contamination in the area where the passive bioventing technology demonstration was conducted are discussed below.

In preparation for full-scale design of a conventional bioventing system at the PFFA, a bioventing pilot test was conducted in the demonstration area prior to demonstration activities in November/December 1997. This pilot test consisted of installing one shallow vent well, PFFAVW01, and three vapor monitoring points, PFFAVMP14, PFFAVMP15, and PFFAVMP16 (Figure 6). Well construction details and boring logs are provided in Appendix C. Figure 6 also shows sampling locations for the demonstration, which are more fully discussed in Section 4.

Soil and soil vapor samples were collected for analysis in conjunction with the installation of the bioventing pilot test wells (PFFAVW01, PFFAVMP14, PFFAVMP15, and PFFAVMP16), the passive bioventing demonstration VW (PFFAVW02), and the buried oxygen sensors (PFFABOS01 through PFFABOS08). The results of these analyses, taken prior to any demonstration activities, are summarized in Tables 2, 3, and 4.

The maximum detected concentrations of soil contaminants were: 28,000 mg/kg total petroleum hydrocarbons as gasoline (TPH-g); 4,400 mg/kg TPH as jet propulsion fuel #4 (TPH-JP4); 2,880 mg/kg TPH as jet propulsion fuel A (TPH-Jet A); 12 mg/kg benzene, 80 mg/kg toluene, 40 mg/kg ethylbenzene, and 180 mg/kg total xylenes. The maximum detected concentrations of soil vapor contaminants were: 54,000 parts per million by volume (ppmv)

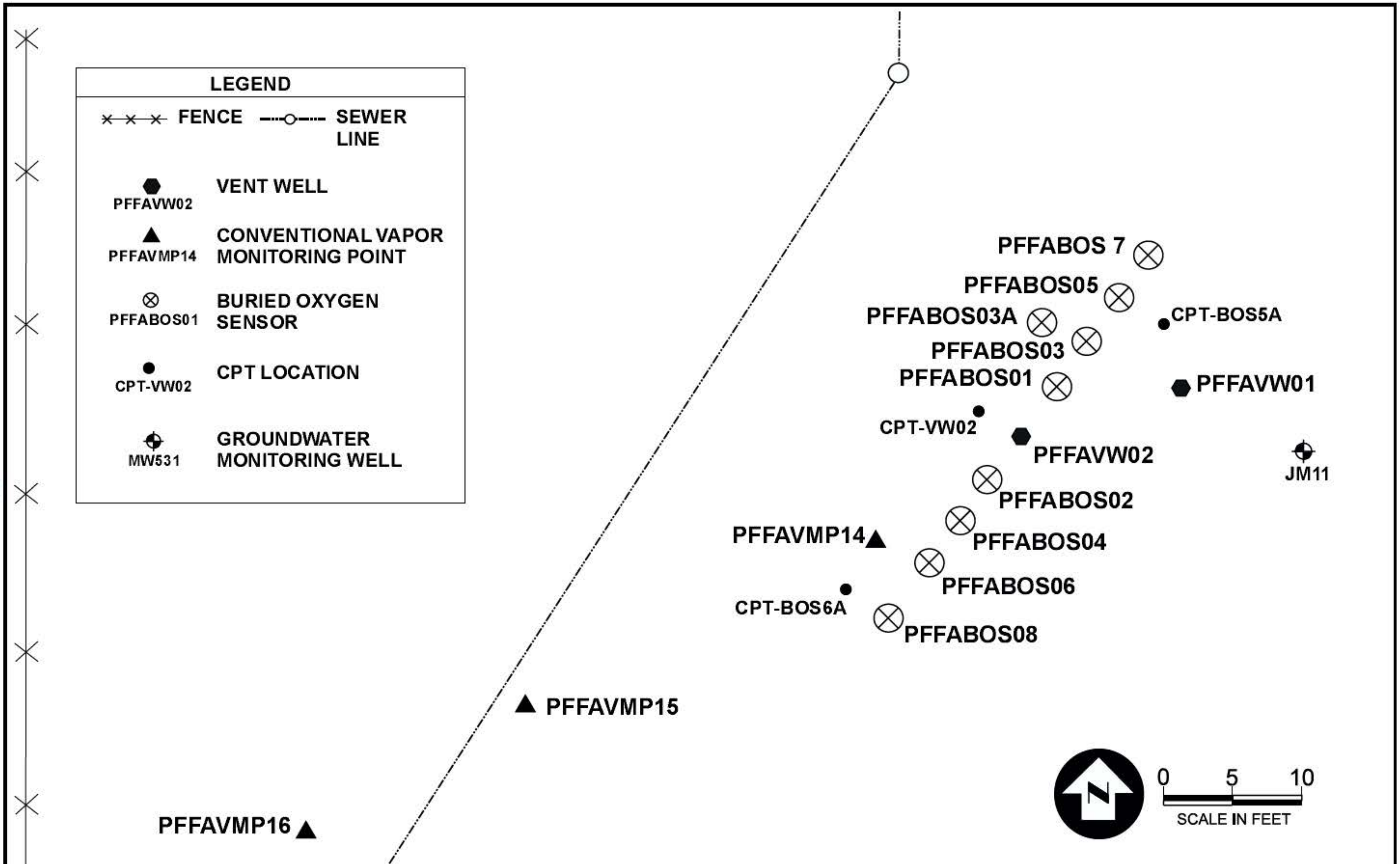

FIGURE 6

SITE PLAN

PFFA
Castle Airport, California

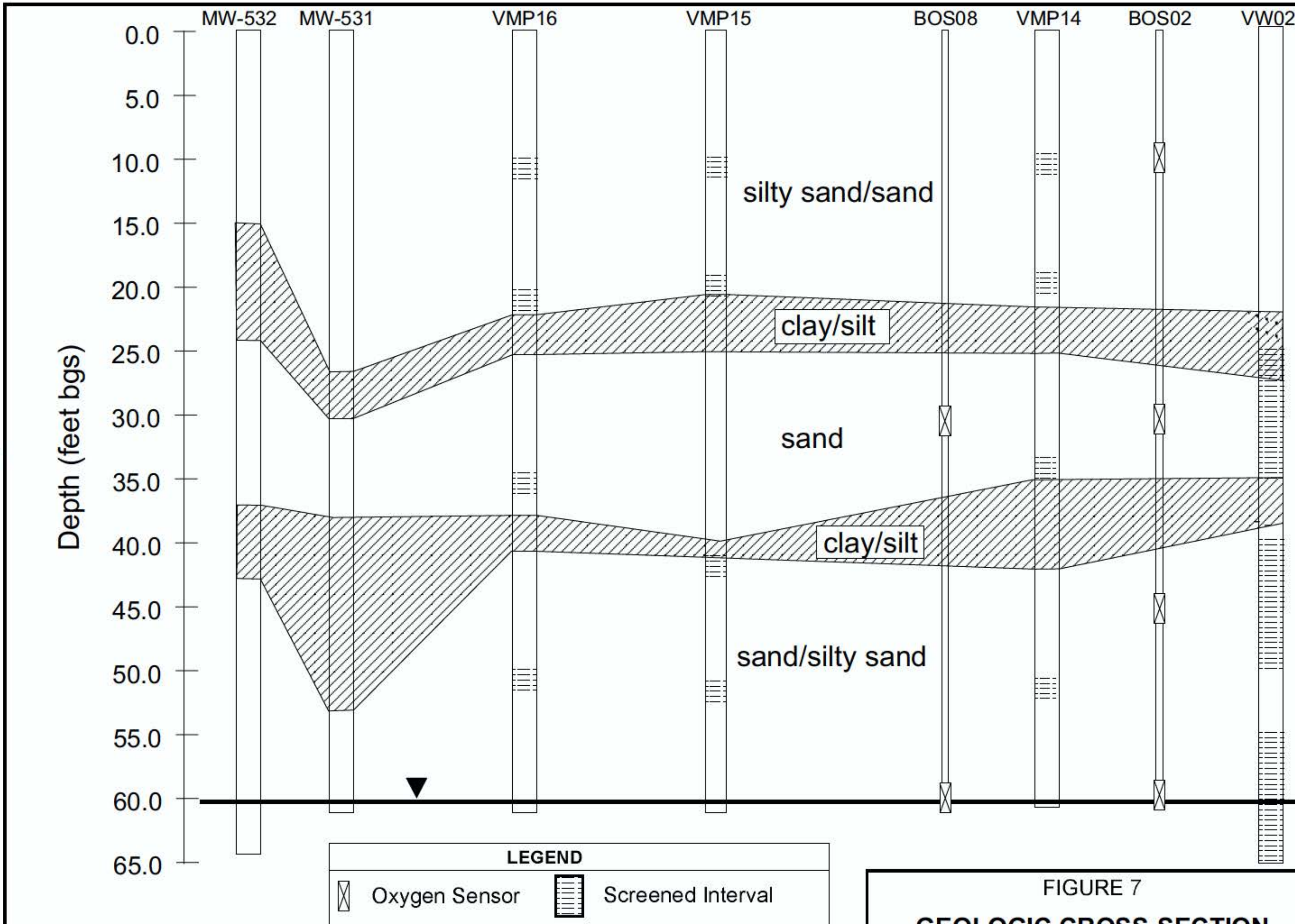

FIGURE 7

GEOLOGIC CROSS-SECTION

\731272\REPORT\FINAL\GRAPHICS\FIGS_L8A.CDR 9/29/00

TABLE 2
Soil Sampling Results - Organics & Moisture Content
PFFA - Castle Airport, California

		Total Petroleum Hydrocarbons				Volatile Organic Compounds				Moisture
	Method:	8015M/8015B				8020A/8260				ASTM D2216
	Analyte:	TPH-g	TPH-JP4	TPH-Jet A	TPH-d [1]	Benzene	Toluene	Ethyl-benzene	Total Xylenes	Moisture Content
Location	Depth (ft bgs)	mg/kg								% by wt
PFFAVW01	20	1.4 J	n.a.	n.a.	2.9 J	0.044	<0.007	0.005	0.008	25.5
	33	1,700. J	n.a.	n.a.	200. J	<0.062	<0.062	3.2	11.2	3.2
PFFAVW02	30	<1.	<1.	<10.	<10.	<0.005	<0.005	<0.005	<0.005	4.6
	45	<500.	0.73	613.	<10.	<2.5	0.6	4.3	19.	3.8
	60	<1.	<1.	<10.	<10.	<0.005	<0.005	<0.005	<0.005	4.6
PFFAVMP14	15	0.84 J	n.a.	n.a.	2.6 J	<0.006	<0.006	<0.002	<0.006	8.7
	22	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	1.9
	40.5	2,200.	n.a.	n.a.	1,000. J	8.1	53.	40.	178.	18.0
	41	28,000.	n.a.	n.a.	490. J	12.	80.	37.	164.	20.4
	51	2.9 J	n.a.	n.a.	130. J	0.021	0.034	0.014	0.054	2.5
PFFAVMP15	43	0.71 J	n.a.	n.a.	n.a.	<0.005	<0.005	<0.002	<0.005	2.4
	52	0.71 J	n.a.	n.a.	1.9 J	0.001 J	<0.005	<0.002	<0.005	3.4
PFFAVMP16	15	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	0.9
	55	0.49 J	n.a.	n.a.	3.1 J	0.002 J	<0.005	<0.002	<0.005	4.6
PFFABOS01	30	<1.	<1.	<10.	<10.	<0.005	<0.005	<0.005	<0.005	3.0
	45	<500.	3,000.	<10.	<10.	<2.5	14.	27.	120.	8.7
	59	<500.	1,200.	323.	<10.	<2.5	0.5 J	3.9	30.	4.5
PFFABOS02	30	<1.	<1.	<10.	<10.	<0.005	<0.005	<0.005	<0.005	5.3
	45	<50.	160.	256.	<10.	<0.25	<0.25	0.22 J	1.1	4.4
	45.5	<500.	360.	290.	<10.	<2.5	<2.5	0.60 J	2.8	3.2
	59	<1.	<1.	<10.	<10.	<0.005	<0.005	<0.005	<0.005	4.5
PFFABOS3A	30	<500.	720.	445.	<10.	<2.5	0.49 J	1.2	3.0	3.6
PFFABOS03	45	<500.	2,200.	<10.	<10.	4.0	37.	25.	99.	3.1
	45.5	<500.	3,400.	<10.	<10.	8.0	58.	34.	140.	3.1
	59	<500.	2,500.	<10.	<10.	0.9 J	19.	16.	100.	6.0
PFFABOS04	30	<1.	<1.	<10.	<10.	<0.005	<0.005	<0.005	<0.005	5.9
	45	<500.	800.	324.	<10.	<2.5	2.9	6.4	29.	7.3
	45.5	<500.	1,200.	<10.	<10.	0.53 J	6.9	10.	45.	4.8
	59	<1.	<1.	<10.	<10.	<0.005	<0.005	<0.005	<0.005	4.4
PFFABOS05	30	<500.	2,000.	1,250.	<10.	<2.5	0.5	12.	28.	3.6
	59	<500.	4,400.	2,880.	<10.	4.4	44.	24.	180.	6.2
PFFABOS06	30	<1.	<1.	<10.	<10.	<0.005	<0.005	<0.005	<0.005	3.4
	59	<1.	<1.	<10.	<10.	<0.005	<0.005	<0.005	<0.005	3.5
PFFABOS07	30	<500.	2,700.	1,800.	<10.	0.5	2.	23.	61.	3.4
	59	<500.	1,200.	775.	<10.	0.4	7.5	5.6	42.	7.2
PFFABOS08	30	<1.	<1.	<10.	<10.	<0.005	<0.005	<0.005	<0.005	4.1
	59	<1.	<1.	<10.	<10.	<0.005	<0.005	<0.005	<0.005	5.6

Notes:

[1] Chromatographic profile for all diesel results was inconsistent with the diesel reference fuel standard.

1.4 J : "J" denotes estimated concentration

n.a. : not analyzed

<10. : Result was less than the indicated reporting limit

TPH-g : Total Petroleum Hydrocarbons in the gasoline range

TPH-JP4 : Total Petroleum Hydrocarbons in the jet propulsion fuel #4 range

TPH-Jet A : Total Petroleum Hydrocarbons in the jet propulsion fuel A range

TPH-d : Total Petroleum Hydrocarbons in the diesel range

TABLE 3
Soil Sampling Results - Inorganics & Physical Properties
PFFA - Castle Airport, California

		Inorganics								Grain-Size Analysis				
	Analyte:	TKN	Total Phos-phorous	Alkalinity	Total Iron	Microbially Reducible Iron	Soluble Iron	ORP	pH	Coarse sand	Med sand	Fine sand	Silt	Clay
	Method:	E351.4M	E365.3M	E310.1M	E6010A	Lovley & Phillips, 1987	DIWET/ E6010A	ASTM D1498-76	E9045C	ASTM D422				
Location	Depth (ft bgs)	mg/kg					ug/L	mV	units	% by weight				
PFFAVW02	30	32.	221.	59. J	7,700.	<2.0	3,040.	174.	7.71	0.1	58.1	25.8	14.7	1.3
	45	50.	227.	<200.	7,010.	8.0	819.	190.	7.80	0.2	51.0	30.5	16.8	1.5
	60	42.	172.	15. J	7,380.	<2.0	1,080.	203.	8.04	0.6	16.2	64.7	17.5	1.0
PFFAVMP14	22	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	0.0	2.3	5.0	59.3	33.4
	40.5	<50.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.
	41	<50.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.
PFFAVMP15	43	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	0.0	17.9	73.3	8.8	0.0
	52	<50.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.
PFFAVMP16	15	59.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	0.6	24.8	44.3	19.9	10.4
PFFABOS02	45	41.	238.	48. J	7,570.	44.	1,040.	164.	7.32	n.a.	n.a.	n.a.	n.a.	n.a.
	45.5	48.	148.	25. J	5,960.	31.	694.	189.	7.30	n.a.	n.a.	n.a.	n.a.	n.a.
PFFABOS07	30	29.	229.	<200.	5,690.	<2.0	2,150.	205.	7.84	0.0	39.6	42.3	16.6	1.5
	59	69.	193.	30. J	10,000.	<2.0	948.	206.	8.13	0.0	6.3	75.0	17.2	1.5

Notes:

2.1 J : "J" denotes estimated concentration
n.a. : not analyzed
<50 : Result was less than the indicated reporting limit

TKN : Total Kjeldahl Nitrogen
ORP : Oxidation Reduction Potential

TABLE 4
Soil Vapor Sampling Results
PFFA - Castle Airport, California

	Method:	EPA TO-3					Field Instruments		
	Analyte:	TPH-g	Benzene	Toluene	Ethyl-benzene	Total Xylenes	TVH	Oxygen	Carbon Dioxide
Location	Depth/Screen Interval (ft bgs)	units in ppmv						units in %	
PFFAVW01	6-21	4,600.	20.	30.	29.	110. J	>10,000.	1.5	12.5
PFFAVW02	25-35;40-50;55-65	20,000.	220.	220.	41.	200.	>10,000.	0.0	8.8
PFFAVMP14	10	n.a.	n.a.	n.a.	n.a.	n.a.	200.	1.5	12.5
	20	n.a.	n.a.	n.a.	n.a.	n.a.	1,500.	0.3	8.0
	35	13,000. (12,000.)	250. (250.)	160. (160.)	50. (42.)	150. (110.)	>10,000.	0.0	12.7
	51	54,000. J	1,200. J	820. J	140. J	440. J	>10,000.	1.0	12.3
PFFAVMP15	10	n.a.	n.a.	n.a.	n.a.	n.a.	260.	12.8	2.5
	20	1,700.	7.2	9.1	10.	44. J	3,100.	0.0	8.0
	42	n.a.	n.a.	n.a.	n.a.	n.a.	>10,000.	0.4	13.2
	52	40,000.	540.	45.	130.	370.	>10,000.	0.0	13.0
PFFAVMP16	10	n.a.	n.a.	n.a.	n.a.	n.a.	1,100.	18.3	2.1
	20	440.	0.72	2.4	1.3	5.5 J	2,000.	4.7	4.5
	35	n.a.	n.a.	n.a.	n.a.	n.a.	7,400.	0.0	13.0
	51	22,000.	230.	47.	48.	110.	>10,000.	0.0	13.0
PFFABOS01	10	260.	0.68	2.0	0.73	2.8	510.	0.0	0.3
	30	8,000.	59.	14.	17.	55. M	>10,000.	0.0	7.0
	45	48,000. (35,000.)	560. (500.)	270. (310.)	53. (21.)	200. (78.) M	>10,000.	0.0	9.0
	59	18,000.	77.	28.	4.6	17. M	>10,000.	0.0	9.5
PFFABOS02	10	250.	0.37	2.2 M	0.60	1.9 M	880.	0.6	0.7
	30	3,600.	20.	18.	12.	42. M	7,100.	0.0	7.0
	45	19,000.	120.	28.	4.8	10. M	>10,000.	0.0	8.8
	59	22,000.	96.	44.	10.	44. M	>10,000.	0.0	9.0
PFFABOS03A	10	78.	0.32	0.50	0.35	1.2	1,000.	0.0	2.3
	30	6,200.	35.	28.	11.	37.	>10,000.	0.0	7.2
PFFABOS03	45	16,000.	96.	28.	4.5	15.	>10,000.	0.0	9.4
	59	22,000.	100.	37.	5.3	13.	>10,000.	0.0	9.8
PFFABOS04	10	180. (87.)	2.8 (1.4)	1.2 (0.83)	0.25 (0.16)	0.85 (0.60)	310.	0.0	1.8
	30	2,200.	8.6	14. M	4.2	14. M	6,800.	0.0	6.9
	45	51,000.	480.	300.	80.	350.	>10,000.	0.0	8.6
	59	17,000.	33.	8.3	4.4	15. M	>10,000.	0.0	9.0
PFFABOS05	30	5,300.	26.	24.	5.7	17. M	>10,000.	0.0	7.5
	59	19,000.	100.	32.	4.4	14.	>10,000.	0.0	10.0
PFFABOS06	30	1,500.	3.7	10.	6.3	16.	4,100.	0.0	6.8
	59	15,000.	82.	15.	5.0	16. M	>10,000.	0.0	9.0
PFFABOS07	30	32,000. (34,000.)	320. (340.)	81. (84.)	190. (210.)	670. (700.)	>10,000.	0.0	7.5
	59	21,000.	100.	30.	6.6	19.	>10,000.	0.0	10.0
PFFABOS08	30	1,200.	1.7	8.6	4.6	10.	3,200.	0.4	6.5
	59	14,000.	48.	12.	6.6	22. M	>10,000.	0.0	8.5
PFFAVMP01	15	n.a.	n.a.	n.a.	n.a.	n.a.	66.	19.4	1.5
	30	n.a.	n.a.	n.a.	n.a.	n.a.	36.	19.0	1.8
MW270	48-89	n.a.	n.a.	n.a.	n.a.	n.a.	6.	19.5	0.8

(34,000.) : duplicate results shown in parentheses

2.1 J : "J" denotes estimated concentration

17 M :"M" denotes result may be biased due to matrix interferences

TVH : Total volatile hydrocarbons

>10,000 : Reading greater than indicated maximum limit of the instrument

TPH-g; 1,200 ppmv benzene, 820 ppmv toluene, 210 ppmv ethylbenzene, and 700 ppmv total xylenes.

In addition to laboratory analyses, soil vapor throughout the area was analyzed in the field for oxygen, carbon dioxide, and total volatile hydrocarbons (TVH) using field meters. These results are also provided in Table 4 and indicate that the soil vapor is oxygen-depleted throughout the area, with the exception of some of the soil vapor in the shallower soils above 20 feet bgs. TVH readings were also lower in the shallower soils.

The soil vapor results generally correlated with the soil results. Soil, soil vapor, and headspace screening results indicate contamination is highest in the deeper soils below 35 to 30 feet bgs and extends to groundwater.

Soil vapor was also analyzed with the field meters at two uncontaminated background locations (PFFAVMP01 and MW270) located approximately 1,300 feet southeast (upgradient) of the site. Results are provided in Table 4. Oxygen concentrations at these locations are above 19.0%, indicating that there is very little natural oxygen demand in the soil and the measured oxygen-depletion in the VW and VMPs is an indication of microbial activity associated with the petroleum-contaminated contaminated soils.

3.2.4 Soil Grain-Size Analysis. Selected soil samples collected from both previous investigations and the demonstration activities were submitted for grain-size analysis to compare against lithologic interpretations made in the field. Samples were collected from the upper silty sand between ground surface and approximately 20 feet bgs, the clay/silt layer between approximately 20 and 25 feet bgs, and the sand layers between approximately 25 and 35 feet bgs and below approximately 40 feet bgs. Results are provided in Table 3. The results generally confirmed the lithologic interpretations made in the field, with significant silt and clay fractions measured in the clay/silt layer (greater than 90% clay/silt) and higher silt and clay fractions measured in the upper silty sand interval above 20 feet bgs (greater than 30% clay/silt) compared to the lower sand intervals (average of 16% clay/silt).

3.2.5 Soil Moisture and pH. Soil moisture and pH were measured for selected soil samples collected during the previous remedial investigations at the PFFA and during the installation of the wells for the demonstration. For vadose zone soil samples, soil moisture content ranged from 0.9 to 25.5 percent by weight (% by wt.), with an average soil moisture content calculated at 5.8%. The moisture content for most samples was between 2% and 10%, a range considered optimal for bioventing since sufficient moisture is available for microorganisms but moisture content is not high enough to limit air permeability or air-filled porosity (USEPA ORD, 1995).

The soil moisture contents reported in Table 2 are relatively consistent when compared against the lithologic zone from which they were collected. For example, the relatively higher moisture contents of 18.0%, 20.4%, 25.5% shown in the table were all collected from the less permeable, clay/silt layers at 20 feet bgs (PFFAVW01) or 41 feet bgs (PFFAVMP14) (see Figure 7). All other moisture contents from the more permeable soils were relatively

consistent, showing a standard deviation of only 1.8% across a range of moisture contents between 0.9% and 8.7%.

Soil pH values were measured between 7.30 and 8.13, within the range considered optimal for microbial activity.

3.2.6 Air Permeability Testing. Air permeability testing was also conducted in the demonstration area during conventional bioventing pilot test activities in December 1997, prior to demonstration activities (Parsons ES, 1998). Two tests were conducted. The first test consisted of injecting air at PFFAVW01 in the shallow, finer-grained materials above 20 feet bgs. The second test consisted of injecting air in MW531 into the deeper, coarser-grained materials below 25 feet bgs. Results from the air permeability tests showed a smaller radius of influence (70 feet) and lower air permeability (3.9 darcies) could be expected in the shallow soils compared to the deeper soils (110 feet and 38 to 200 darcies). These results are consistent with the stratified geology of the site, as discussed in Section 3.2.2 and shown on Figure 7. The air permeabilities in both lithologic zones are within the range considered suitable for bioventing (USEPA ORD, 1995).

3.2.7 *In Situ* Respiration Testing. Short-term, initial *in situ* respiration (ISR) tests were also conducted in the demonstration area during conventional bioventing pilot test activities in February 1998, prior to demonstration activities (Parsons ES, 1998). The ISR tests were conducted at PFFAVMP14, PFFAVMP15, and PFFAVMP16. Testing was conducted at two discrete depth screens at PFFAVMP14 (35 feet and 51 feet bgs), one discrete depth screen at PFFAVMP15 (42 feet bgs), and one discrete depth screen at PFFAVMP16 (35 feet bgs). The purpose of using multi-depth monitoring points was to verify that soil bacteria and oxygen demand were present within the entire vadose zone. Subsequent ISR testing was also conducted during the demonstration; ISR test results from the demonstration are discussed in Section 5.2.3.

Results from the initial ISR tests indicate there were active microorganism populations within the oxygen-depleted zones that were tested. Initial oxygen-utilization rates measured at the demonstration area were low to moderate, ranging from 0.087% oxygen per hour (% O_2/hr) (2.1 %O_2/day) at PFFAVMP15 at 42 feet bgs to 0.29% O_2/hr (7.0% O_2/day) at PFFAVMP14 at 35 feet bgs, with a mean rate at all tested locations of 0.18% O_2/hr (4.2% O_2/day).

3.2.8 Barometric Pressure, Air Flow, and Differential Pressure. During the installation of the VW and VMPs for the conventional bioventing pilot test, it was noted by the field geologist that the VMPs and MWs at the site were exhaling and inhaling air at various times during the day. In addition, during the air permeability testing, the field scientist noted that changes in barometric pressure were clearly affecting the pressure measurements used to infer radius of influence and calculate air permeability. The barometric pressure interference was so significant (resulting in subsurface differential pressure fluctuations in the VMPs on the order of 0.3 to 0.6 inches of water) that subsurface differential pressure in a background well needed to be measured periodically to correct for the interference.

Based on these observations, a short test was conducted to evaluate the effect of barometric pressure on subsurface differential pressure and air flow at the site. Details are provided in the Technology Demonstration Plan, Site-Specific Addendum (NFESC, 1998). Air flow as high as 11 cfm and differential pressures as high as 0.9 inches H_2O were observed. Barometric pressure had a clear effect on both air flow and differential pressure, with air flowing into the well during periods of increasing air pressure and air flowing out of the well during periods of decreasing air pressure. Both long-term weather front changes and short-term diurnal changes affected both air flow and subsurface differential pressure.

Based on these results, more extensive testing to determine the radius of oxygen influence due to barometrically-induced air flow was of interest and the PFFA was selected as the passive bioventing demonstration site.

4. Demonstration Approach

4.1 Performance Objectives

As discussed in Section 2.1.5, the two primary performance objectives for this demonstration project were:

1. Achieve an adequate radius of influence to be economically viable; and,
2. Achieve air flow rates sufficient to meet the biological demand.

Because the radius of influence and oxygen demand of microorganisms will be site-specific, the success of the technology will necessarily be based on the ability to achieve an economical radius of influence from VWs and induce air flow needed to meet site-specific oxygen demands rather than on presumptive numerical values. The treatment area and air flow requirements must be met economically, without an excessive number of VWs required compared to a conventional bioventing approach.

Based on calculations and previous passive bioventing studies detailed in the TDP (NFESC, 1997), peak air flow rates on the order of 1 cubic foot per minute (cfm) per well or more, total air flow rates on the order of 1,200 cfd per well or more, and a radius of influence on the order of 10 feet per well or more are the expected results that will indicate the technical and economic success of the passive bioventing technology.

4.2 Physical Setup and Operation

4.2.1 Vent Well Construction. The initial phase of the demonstration conducted in March 1998 consisted of installing one vent well (PFFAVW02) (Figure 6). The VW was installed using hollow-stem augering (HSA) techniques and was constructed of 4-inch inside diameter (ID) Schedule 40 polyvinyl chloride (PVC) casing and 0.04-inch slotted screens. The VW was screened between 25 and 65 feet bgs, below the near surface silty sand and clay/silt layers

(Figure 7). Three individual, isolated 10-foot screened intervals were used in the VW in order to evaluate air flow rates into the different lithologic environments at the site. Each of the screens is isolated using solid PVC casing and corresponding bentonite seals between the screened sections and sand filter packs. These screens and their relationship to the lithologic zones at the site are shown on Figure 7. Construction details for the VW are provided on Figure 8 and a boring log/well construction detail is provided in Appendix C.

4.2.2 Buried Oxygen Sensors/Vapor Monitoring Points. Following installation of the VW, eight VMPs consisting of two radial arms each with four VMPs, were installed adjacent to the VW (Figure 6; Appendix E). Initially, it was planned to install the VMPs using cone-penetrometer test (CPT) techniques to save on costs and expedite the installation schedule. However, refusal of the CPT occurred during installation of the initial VMPs and some of the boreholes also collapsed during installation, which prevented accurate borehole verticality measurements (discussed in Section 4.2.3). Therefore, the CPT boreholes were grouted in place and HSA techniques were used in the final construction of all VMPs.

The four VMPs along each arm are located at distances of approximately 4, 8, 12, and 16 feet from PFFAVW02. Each of the VMPs is constructed using directly-buried oxygen sensors with an integrated sampling and pressure measurement port (Datawrite Research Corp. model XTM253SP) strapped to 2-inch ID solid PVC casing running the length of the borehole (Figure 9). Sensors at the four innermost VMPs (*i.e.,* those located at 4 and 8 feet from the PFFAVW02) are installed at approximately 10, 30, 45, and 60 feet bgs. Sensors at the remaining four VMPs (*i.e.,* those located at 12 and 16 feet from the PFFAVW02) are installed at approximately 30 and 60 feet bgs. Each of the sensors is isolated at depth using bentonite seals between the sensors and sand filter packs. The sensor depths and their relationship to the lithologic zones at the site and the screened intervals of PFFAVW02 are shown on Figure 7. Typical construction details for the VMPs are provided on Figure 9.

During sensor installation at PFFABOS03, the tubing connected to the two shallowest buried oxygen sensors (*i.e.,* those at 10 and 30 feet bgs were accidentally destroyed while removing the hollow-stem augers. Therefore, these two damaged sensors were abandoned in place and replaced by two sensors installed in another borehole (subsequently named PFFABOS03A) adjacent to and at the same distance from PFFAVW02 as PFFABOS03. For simplicity, in the remainder of this report no distinction is made when discussing in the text whether the sensors located at the 8-foot distance along the northeastern arm are located in borehole PFFABOS03 or borehole PFFABOS03A.

CPT traces from successful CPT boreholes installed at the site are provided in Appendix C; CPT locations are shown on Figure 6. Results from the limited CPT installation were consistent with the geologic conceptual model (Section 3.2.2) determined from installation of the VW and conventional VMPs (PFFAVMP14, PFFAVMP15, and PFFAVMP16).

4.2.3 Borehole Verticality Survey. After installation of the VW and VMPs, a borehole verticality survey was conducted by Norcal Geophysical (Petaluma, California) using a Robertson Geologging, Ltd. verticality probe. As discussed in the Technology Demonstration

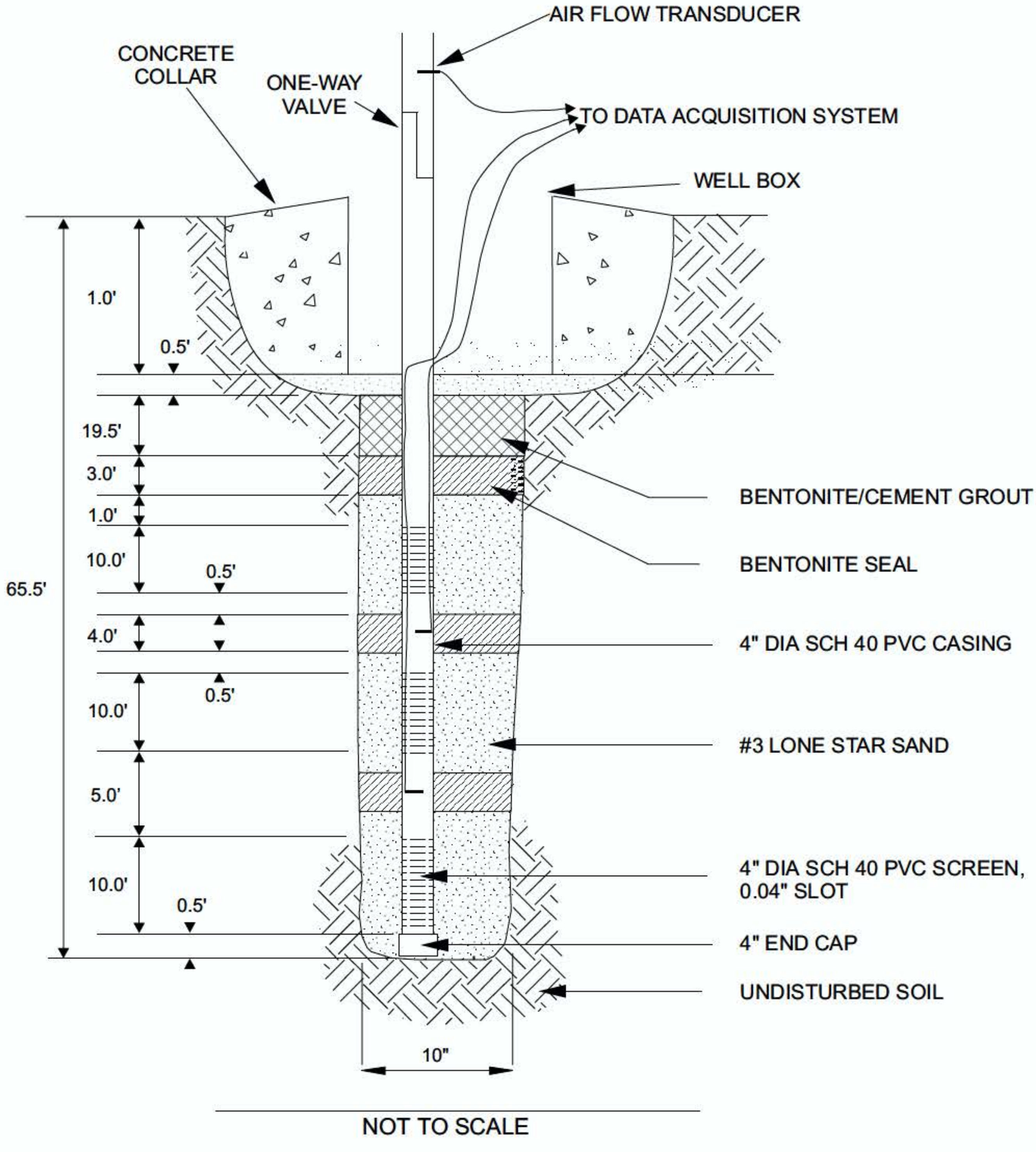

FIGURE 8
VENT WELL CONSTRUCTION AND AIR FLOW TRANSDUCER PLACEMENT

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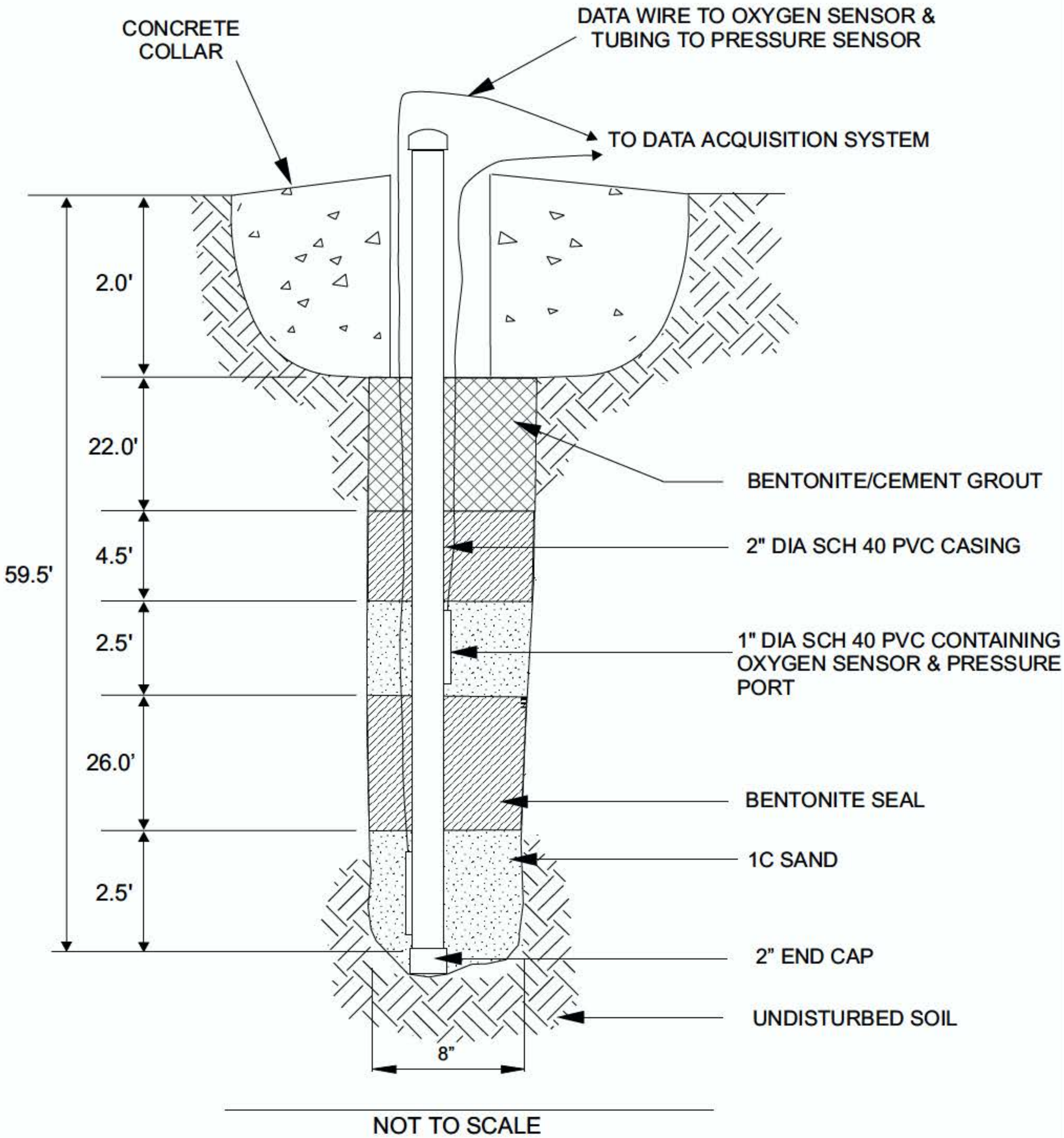

FIGURE 9

BURIED OXYGEN SENSOR DETAIL (TYPICAL)

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Castle Airport, California

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Plan, Site-Specific Addendum (NFESC, 1998), the primary purpose of the verticality survey was to ensure the vertical orientation of the borings and correct for any significant deflection or intrusion into the sand filter pack of nearby VW/VMPs. The verticality survey was considered important since the distance between the VMPs and between the innermost VMPs and the VW was only 4 feet.

The results of the verticality survey are provided in Appendix C. Deviations from vertical ranged between approximately 0.10 and 1.1 feet. The deviations generally increased with depth. The largest deviations (1.1 feet) occurred at PFFABOS02 and PFFABOS08, located at 4 and 16 feet from the VW, respectively, at 59 feet bgs. While the maximum deviations at these locations were relatively significant compared to the horizontal distance to the nearest VMP or VW (4 feet), the direction of the deviation was generally away from the nearest VMP or the VW and the distance was not large enough to suspect that borehole interference or overlap occurred, especially at the shallower depths. Therefore, the vertical deviation of each of the boreholes is not expected to have adversely impacted test results or conclusions.

4.2.4 Pressure Transducers, Air Flow Transducers, and Temperature. Bidirectional pressure transmitters (Dwyer model 607) were used to measure subsurface differential pressure at each of the 24 integrated pressure measurements ports connected to the buried oxygen sensors. Three air flow transducers (TSI model 8475) were installed to measure air flow into and out of the VW at different depth intervals. One of the transducers was installed at the surface to measure total air flow; the remaining two were installed between the screened intervals in the VW to allow calculation of air flow into each of the screened sections. The placement of the air flow transducers is shown on Figure 8. Equipment details are provided in Appendix F.

A K-type thermocouple (Cole-Parmer Digi-Sense Model 8528-40) was used to measure ambient temperature at the surface. A downhole pressure transducer (Instrumentation Northwest Model PS9000) was installed in monitoring well JM11 (Figure 6) in order to measure changes in groundwater elevation.

4.2.5 One-Way, Passive Valve Construction. A one-way, passive valve (Section 2.1.3 and Figure 4) was constructed and used during testing to enhance the potential treatment radius. The valve was constructed of 4-inch ID, clear PVC by Nisei Plastics (Oakland, California). During the first two weeks of testing with the passive valve, single-celled foam rubber was used as the material for the internal flow control seal in the valve. However, test results indicated that some leaking was occurring with this material. A passive valve using a mylar sheet was subsequently substituted and used for the remainder of the demonstration tests.

4.2.6 Data Acquisition System. A data acquisition system was installed consisting of multiple data loggers (In-Situ, Inc. Hermit models 2000/3000) to provide enough channels for each of the transducers. The data acquisition system also included an integrated barometric pressure sensor. All measurements were collected and stored in real time. The following data was collected every 10 minutes:

- barometric pressure;
- air flow rates (total and between the three screened intervals in the VW);
- subsurface differential pressure at each VMP screen;
- subsurface oxygen concentration at each VMP screen (directly-buried sensors);
- ambient air temperature; and,
- groundwater elevation.

Installation of the VW, VMPs, and the data acquisition system was completed in April 1998.

4.2.7 Testing and Operation. Following installation of the VW, VMPs/directly-buried sensors, and the data acquisition system, the demonstration was conducted over a six-month period (starting in late April 1998 and continuing through late October 1998). A total of six tests were conducted:

Table 5
Test Configurations and Dates

Test Name	Test Configuration	Dates
TEST 1	PFFAVW02 closed (control)	30 Apr - 13 Jun
TEST 2	PFFAVW02 open without passive valve installed	14 Jun - 02 Jul
TEST 3	PFFAVW02 closed (respiration testing and equilibrium resting period)	02 Jul - 15 Jul
TEST 4	PFFAVW02 open with passive valve installed	16 Jul - 06 Sep
TEST 5	PFFAVW02 closed (equilibrium resting period in preparation for TEST 6)	06 Sep - 03 Oct
TEST 6	PFFAVW02 open without passive valve installed; repeat of TEST 2	03 Oct - 30 Oct

Test 1 was designed to evaluate the effects of barometric pressure fluctuations on subsurface oxygen and pressure conditions without any system enhancement and was used as a control condition for all subsequent tests and for testing system operation. Test 2 was designed to establish a radius of influence from air movement both into and out of the VW, without the use of the passive valve. Test 3 was designed to collect additional respiration data and allow subsurface oxygen concentrations to reach equilibrium concentration prior to the initiation of Test 4. Test 4 was the primary test for the passive bioventing demonstration and evaluated the effect of the passive valve on the radius of influence.

At the end of Test 4, an analysis of the data from Test 2 (discussed in Section 5.2.2) indicated that a repeat of the configuration used in Test 2 was needed due to weather-related barometric pressure changes. Therefore, Tests 5 and 6 were conducted.

4.3 Sampling Procedures

As detailed in the TDP (NFESC, 1997), the passive bioventing demonstration conformed to the maximum extent practical the field protocols and applicable requirements of the most current

version available of the following guidance documents (hereinafter referred to as "protocol documents"):

- *Principles and Practices of Bioventing*, USEPA Office of Research and Development (ORD), EPA/540/R-95/534, September 1995.
- *Test Plan and Technical Protocol for a Field Treatability Test for Bioventing*, U.S. Air Force Center for Environmental Excellence (AFCEE), May 1992.
- *Addendum One to Test Plan and Technical Protocol for a Field Treatability Test for Bioventing - Using Soil-Gas Surveys to Determine Bioventing Feasibility and Natural Attenuation Potential*, AFCEE, February 1994.
- *A General Evaluation of Bioventing for Removal Actions at Air Force/Department of Defense Installations Nationwide*, Air Force Center for Environmental Excellence (AFCEE), June 1996.

Soil and soil vapor contaminant concentrations were measured following the sample collection and analysis techniques specified in the TDP and the Sampling and Analysis Plan (SAP) included in the TDP Site-Specific Addendum (NFESC, 1998). Details on the field meters, sensors, and calibration procedures also are provided in the TDP Site-Specific Addendum. The field procedures and calculations used for measuring air permeability of the soil, measuring *in situ* respiration rates, and calculating biodegradation rates are well-documented in the protocol documents referenced above.

Changes in soil vapor oxygen concentration with time and distance from the VW were used to determine the radius of influence of the system. To facilitate this evaluation, oxygen concentrations were measured at VMPs located in two directions and several distances from the VW. These measurements were collected in both the VMPs containing directly-buried oxygen sensors (PFFABOS01 through PFFABOS08), as well as the conventional bioventing VMPs (PFFAVMP14, PFFAVMP15, and PFFAVMP16) previously installed at the demonstration site.

4.4 Analytical Procedures

The selection of analytical methods was detailed TDP Site-Specific Addendum. There were no significant deviations from these methods. All methods which were used for soil and soil vapor sampling were USEPA or ASTM standard methods, except for bioavailable (reducible) iron. The method of Lovley and Phillips (1994) was used for this measurement. The analytical methods used for each measurement are summarized in Tables 2, 3, and 4.

5. Performance Assessment

5.1 Performance Data

5.1.1 Soil and Soil Vapor Contaminant Concentrations. Soil and soil vapor contaminant concentrations were presented and discussed in detail in Section 3.2.3 and Tables 2, 3, and 4. These results indicate that sufficient contaminant concentrations and anaerobic conditions existed at the site to facilitate the demonstration and measure a radius of influence based on increases in soil vapor oxygen concentrations.

5.1.2 Soil Moisture and pH. Soil moisture and pH were presented and discussed in detail in Section 3.2.4 and Tables 2 and 3. These results indicate that moisture content and pH were with the ranges considered optimal for bioventing.

5.1.3 Soil Nutrients. Nutrients required for microbial activity and which might be expected to limit microbial activity in subsurface environments include nitrogen, phosphorus, and iron. Selected soil samples collected during the installation of the VW and VMPs at the demonstration site were analyzed for total Kjeldahl nitrogen (TKN), total phosphorus, and total and soluble iron. These results are presented in Table 3.

Nutrient concentrations ranged from 32 mg/kg to 69 mg/kg TKN, 148 mg/kg to 238 mg/kg total phosphorus, 5,690 mg/kg to 10,000 mg/kg total iron, and 694 ug/L to 3,040 ug/L soluble iron. The concentrations of these nutrients are within the ranges considered sufficient for microbial activity (USEPA ORD, 1995) and indicate that available nutrients should not be limiting to microbial activity. Background concentrations of oxygen (discussed in Section 3.2.3 and presented in Table 4) indicated that any natural iron in the soils at the PFFA does not create significant background oxygen demand.

5.1.4 Alkalinity. Soil alkalinity, along with soil pH, is a standard measurement conducted at bioventing sites because alkalinity and pH can affect the evolution of carbon dioxide produced during microbial activity. Alkalinity and pH affect soil vapor carbon dioxide concentrations such that, in high alkalinity soils, carbon dioxide production appears to be low due to the formation of carbonates. Conversely in low alkalinity soils, carbon dioxide production correlates well with oxygen consumption.

Soil alkalinity was measured primarily for comparison of alkalinity at the PFFA to data from other bioventing test sites. Soil alkalinity at the demonstration site in all cases was less than 200 mg/kg (the laboratory reporting limit), although for some samples estimates were provided of between 15 mg/kg and 59 mg/kg (Table 3). These results are consistent with the relatively high carbon dioxide concentrations measured in soil vapor at the site (Table 4) and are at the low end of concentrations measured at other bioventing test sites (USEPA ORD, 1995).

5.1.5 Oxidation Reduction Potential and Microbially Reducible Iron. Oxidation Reduction Potential (ORP) and microbially reducible iron were also measured for selected soil samples.

These measurements are not part of standard bioventing protocols; however, highly reduced soils and significant concentrations of reduced iron could potentially result in significant oxygen demand and increase the oxygen delivery requirements for a passive system. ORP ranged from 164 mV to 206 mV and reducible iron ranged from less than 2.0 mg/kg (the laboratory detection limit) to 44 mg/kg (Table 3).

Reducible iron concentrations were higher in the samples collected from 45 feet bgs, where soil contaminant concentrations were also highest, possibly indicating that some oxygen demand at these locations would occur due to the potential for reduced iron. However, the reducible iron concentrations were significantly less than the contaminant concentrations at those locations and, based on stoichiometry, would result in an oxygen demand far less than that required for microbial breakdown of the contaminants. Based on the ORP and reducible iron concentration data, the soils do not appear to be highly reducing nor are they expected to produce oxygen demands in excess of those predicted from respiration test data.

5.1.6 Barometric Pressure, Air Flow, Subsurface Differential Pressure, Subsurface Oxygen Concentrations, Ambient Air Temperature, and Groundwater Elevation. As discussed in Section 4.3, the following data was collected in real time at 10-minute intervals and stored in the data acquisition system:

- barometric pressure;
- air flow rates (total and between the three screened intervals in the VW);
- subsurface differential pressure at each VMP screen;
- subsurface oxygen concentration at each VMP screen (directly-buried sensors);
- ambient air temperature; and,
- groundwater elevation (at JM11).

All test data from the data acquisition system was downloaded and summarized using computerized spreadsheets (Microsoft Excel). This data is provided in Appendix D and discussed in Section 5.2.

5.2 Data Assessment

5.2.1 Test 1. Test 1 was designed to evaluate the effects of barometric pressure fluctuations on subsurface oxygen and pressure conditions without any system enhancement and was used as a control condition for all subsequent tests and for testing system operation. A plot of subsurface pressure response due to changes in barometric pressure during Test 1 is shown on Figure 10. The plot shows both diurnal barometric pressure changes as well as a minor weather front-related barometric pressure increase (between 28 May and 31 May).

Subsurface differential pressure response is shown for 2 depths, 10 feet bgs and 30 feet bgs. Although the data presented on Figure 10 is from 10 feet bgs and 30 feet bgs at one sampling location (PFFABOS02), it is representative of what is occurring at these depths throughout the site. Data from the same depths at other distances or locations, if plotted, would be indistinguishable from the data presented on Figure 10.

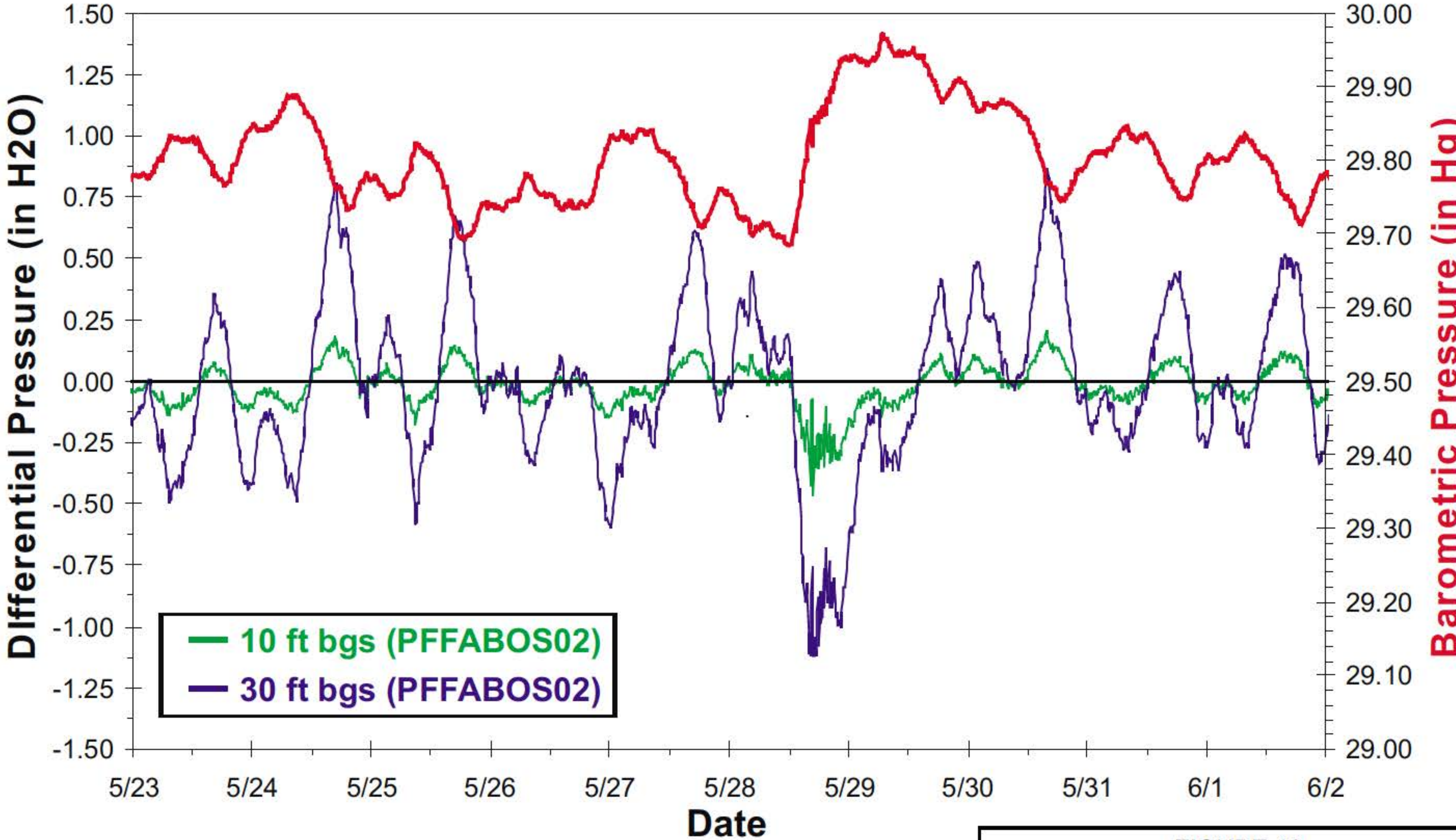

FIGURE 10

SUBSURFACE PRESSURE RESPONSE DURING TEST 1

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As expected, the differential pressure is negative at both depths during periods of increasing barometric pressure (compare to Figure 3) and positive during periods of decreasing barometric pressure. The magnitude of the subsurface differential pressure is significantly greater at 30 feet bgs compared to 10 feet bgs. However, the magnitude of the response at 30 feet bgs was essentially identical to that at 45 feet and 60 feet bgs in all VMPs (a plot of the data from 45 and 60 feet bgs would be indistinguishable on Figure 10 from the data at 30 feet bgs). Therefore, the significant influence on subsurface differential pressure factor at this site is not depth, but rather the geological stratification, more specifically, the overlying lower permeability silty sand between 0 and approximately 20 feet bgs and clay/silt layer between approximately 20 and 25 feet bgs (Figure 7).

5.2.2 Test 2. Test 2 was designed to establish natural rates of air flow into and out of the VW and a radius of influence from this cyclical air movement without the use of the passive valve. A plot of total air flow from PFFAVW02 due to changes in barometric pressure is shown on Figure 11. The plot shows a relatively significant weather front-related barometric pressure change during the first three days of the test, followed by primarily diurnal barometric pressure changes. Both the weather-front and diurnal barometric pressure changes resulted in significant air flow rates both into and out of the VW. Air flow rates as high as 20 cfm occurred during the weather front changes and as high as 12 cfm occurred during diurnal changes. These air flow rates are comparable to typical air flow rates used during conventional bioventing (USEPA ORD, 1995) and demonstrate the feasibility of using a passive bioventing approach at this site.

Air flow was approximately equal between the upper screened interval and the middle screened interval (see Figure 8). Air flow into the lower screened interval was generally much lower compared to flow into the two upper intervals (generally less than 5% of the total flow and never exceeding 18% of the total flow). This is likely a result of the shorter length of exposed screen (only 5 feet was exposed above groundwater; see Figure 7) and because the screen was probably within the capillary fringe.

A plot of oxygen concentrations along the southwestern VMP arm during Test 2 at 30 feet bgs is shown on Figure 12. Oxygen concentrations increased rapidly from near zero and were sustained at greater than 12% at the VMPs located within 8 feet of the VW and greater than 6% at the VMPs located within 16 feet of the VW. Oxygen concentrations did not increase appreciably in the VMP screens which were installed at 10 feet bgs and located within the upper silty sand, indicating that the clay/silt layer at 20 to 25 feet was acting, as expected, as a confining layer to vertical air flow (the VW was not screened within the upper silty sand).

While there was some variability in the oxygen concentrations along the two VMP arms, the differences were not significant. For simplicity, only the data from the southwestern arm is displayed on the figures subsequently presented in this section.

While these results were a positive indication that air flow rates could significantly increase oxygen concentrations at significant distances from the VW, an adequate measure of the radius

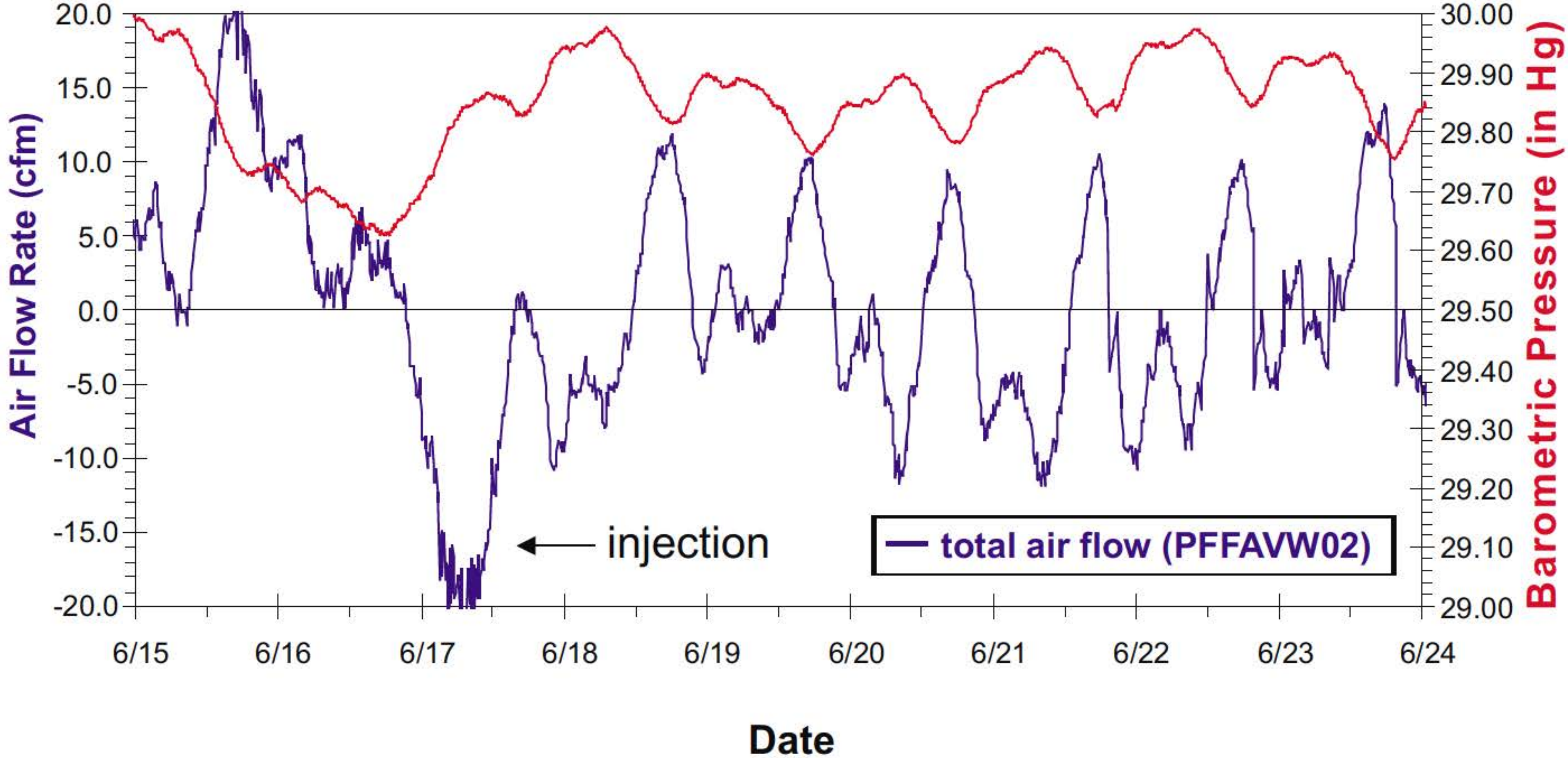

FIGURE 11

AIR FLOW vs. BAROMETRIC PRESSURE DURING TEST 2

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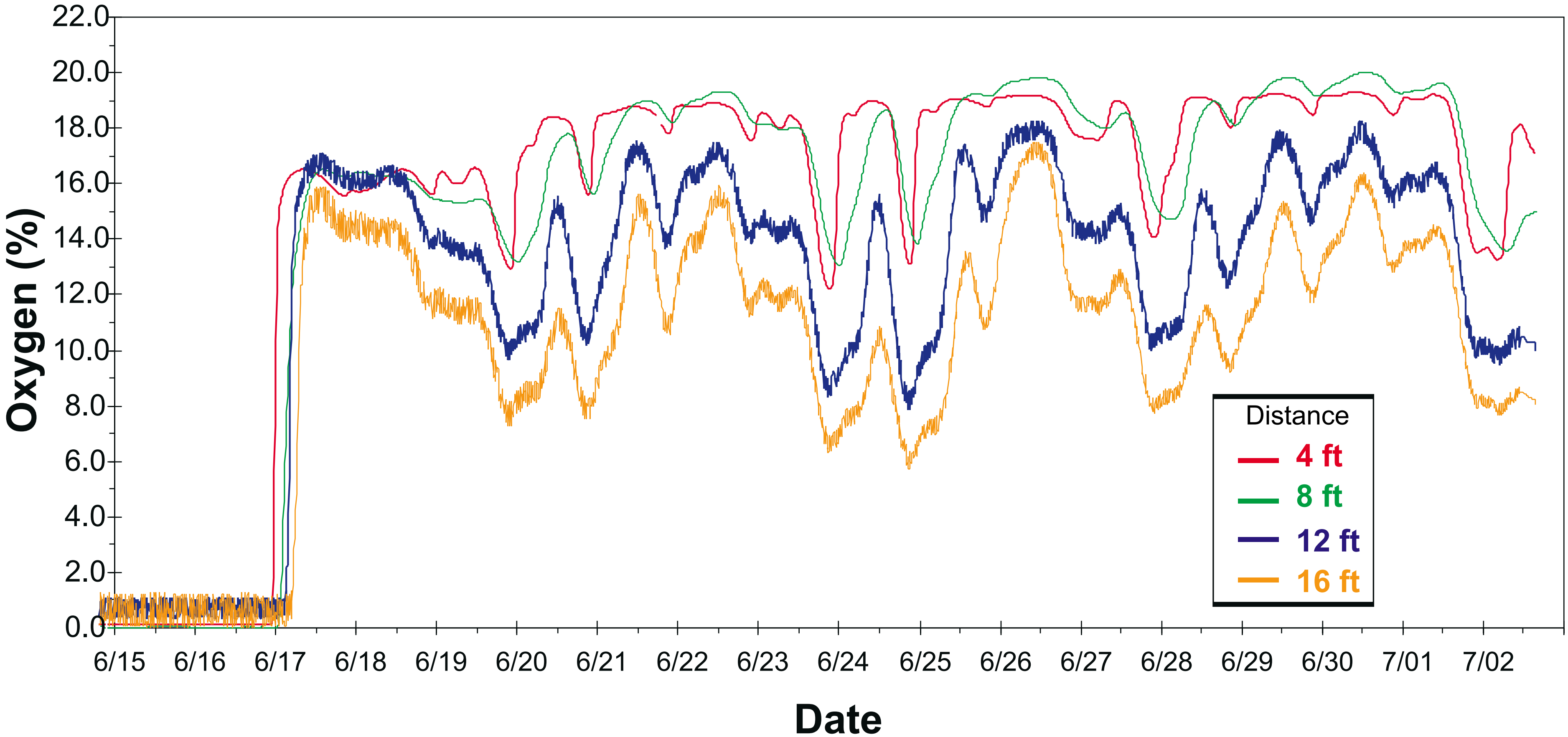

FIGURE 12

OXYGEN RESPONSE AT 30 FEET BGS DURING TEST 2

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of influence was not possible since 5% is typically the oxygen concentration used to indicate that microbial activity is not oxygen limited (*i.e.,* the radius of influence could only be determined to be greater than 16 feet). In addition, the significant air flow which occurred during the weather-front related barometric pressure changes appeared to have been responsible for the significant initial increases in oxygen concentration which prevented an evaluation of oxygen response solely due to diurnal barometric pressure response.

5.2.3 Test 3. Test 3 was designed to collect additional respiration data and allow subsurface oxygen concentrations to reach equilibrium concentration prior to the initiation of Test 4. A plot of oxygen concentrations during Test 3 is shown on Figure 13. Oxygen concentrations decreased to near zero within two weeks at most locations and depths. Field measurements were also conducted to confirm readings from the buried oxygen sensors prior to the start of Test 4.

The rate of decline in oxygen concentrations resulted in calculated oxygen utilization rates between 0.48% O_2/day and 1.5% O_2/day (average rate of 1.0% O_2/day), somewhat lower than the rates measured during the previous short-term ISR tests (Section 3.2.7). However, it is common for such “area” respiration tests as conducted during Test 2, where a significant volume of soil is aerated, to show lower respiration rates than “point” respiration tests, as conducted during the initial ISR testing.

5.2.4 Test 4. Test 4 was the primary test for the passive bioventing demonstration and evaluated the effect of the passive valve on the radius of influence. A plot of air flow response due to changes in barometric pressure during Test 4 is shown on Figure 14. The effect of the passive valve in promoting air flow into the subsurface (a negative sign convention is used to indicate flow into the subsurface) but minimizing air flow out of the subsurface is indicated on this figure. There was some leakage through the valve during the first two weeks of testing (between 16 July and 01 August). Subsequent modifications to the valve (described in Section 4.2.5) reduced the leakage problem for the remainder of the test.

During Test 4 daily air flow rates ranged from a minimum of 27 cfd to a maximum of 9,300 cfd, with an average daily air flow rate of 3,400 cfd (Figure 15). It should be noted, however, that the minimum daily air flow rate of 27 cfd was the only daily air flow rate less than 300 cfd throughout the entire seven week test period. Peak daily air flow rates ranged from 5.1 cfm to 15 cfm, although air flow rates near the daily peak air flow rate were rarely sustained for more than 30 minutes to an hour.

A plot of subsurface oxygen response at 30 feet bgs along one of the VMP arms (PFFABOS02 through PFFABOS08) during Test 4 is shown on Figure 16. As expected, there is a progressive increase in the time for the oxygen response to occur related to the distance from the injection point. However, within a relatively short period of time oxygen concentrations increased from less than 1% to greater than 15% at each VMP. Concentrations greater than 15% were sustained for the entire duration of the test at 30 bgs and concentrations greater than 10% were sustained at 45 feet bgs.

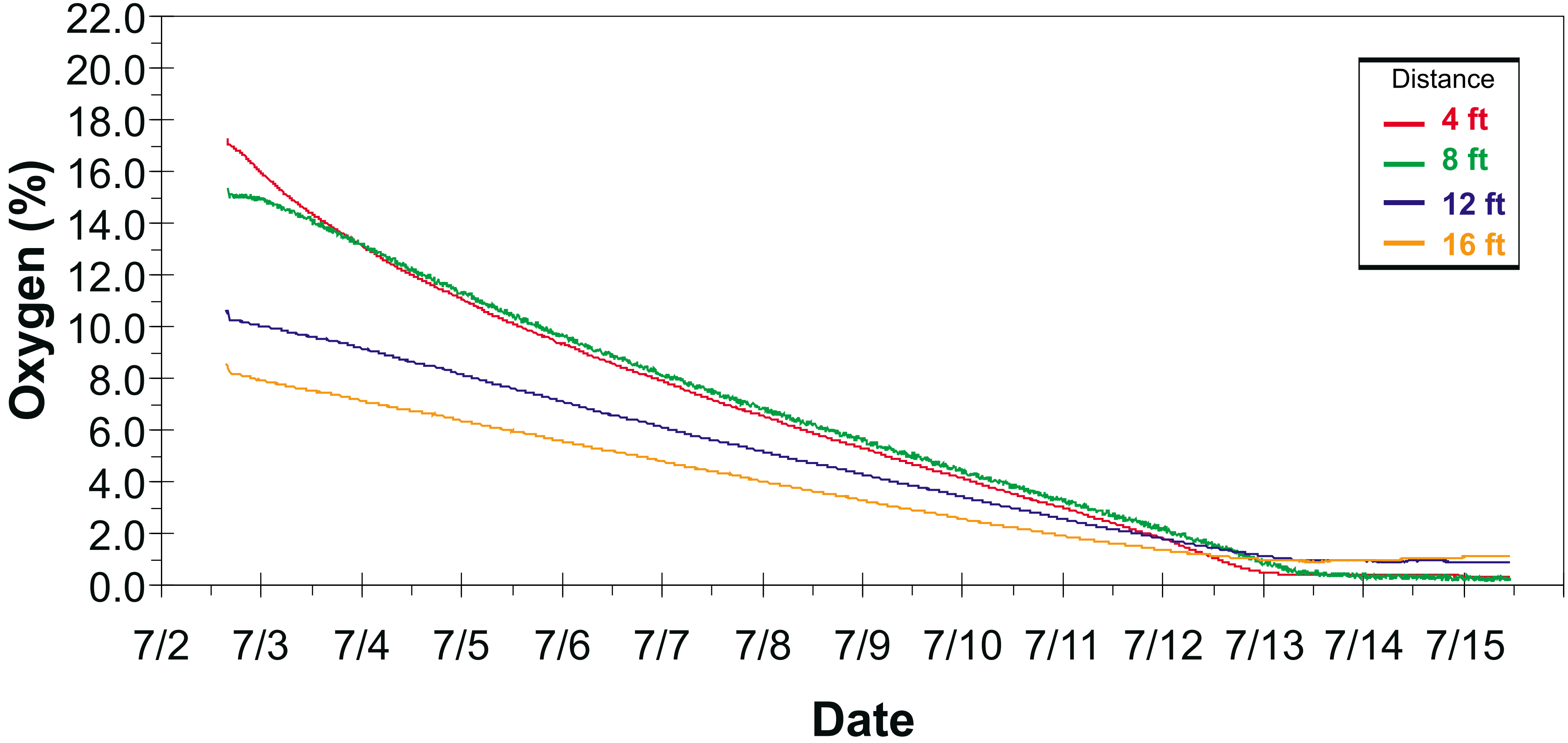

FIGURE 13

OXYGEN RESPONSE AT 30 FEET BGS DURING TEST 3

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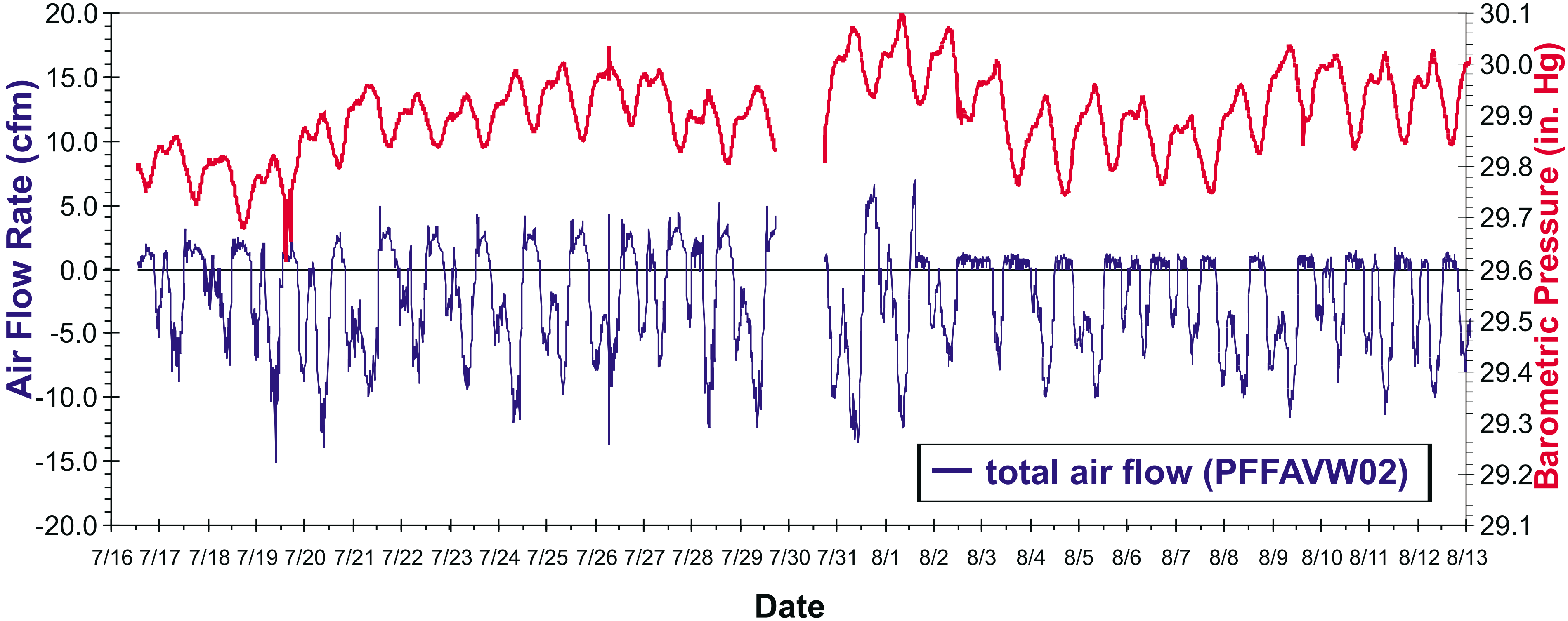

FIGURE 14

AIR FLOW vs. BAROMETRIC PRESSURE DURING TEST 4

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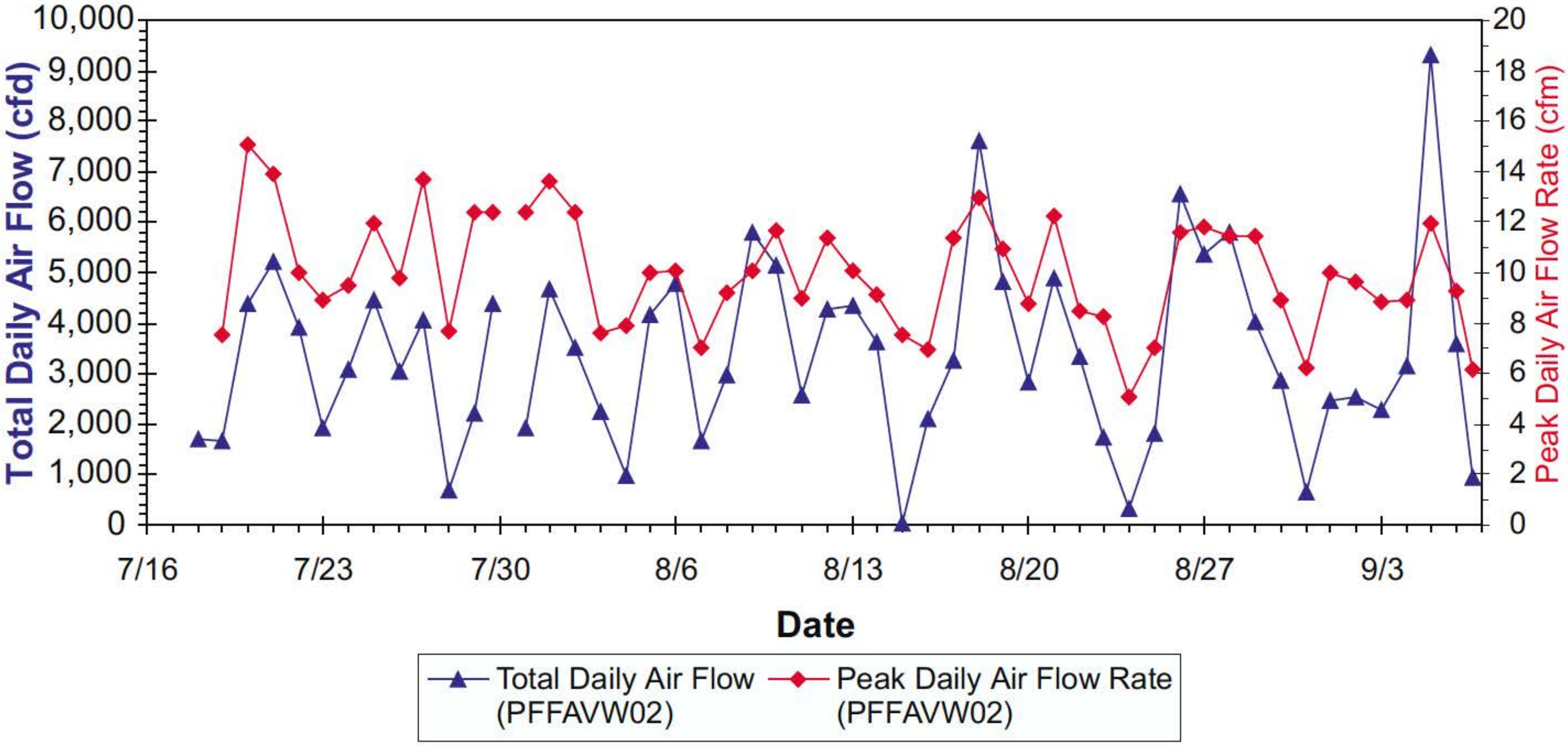

FIGURE 15

DAILY AIR FLOW RATES DURING TEST 4

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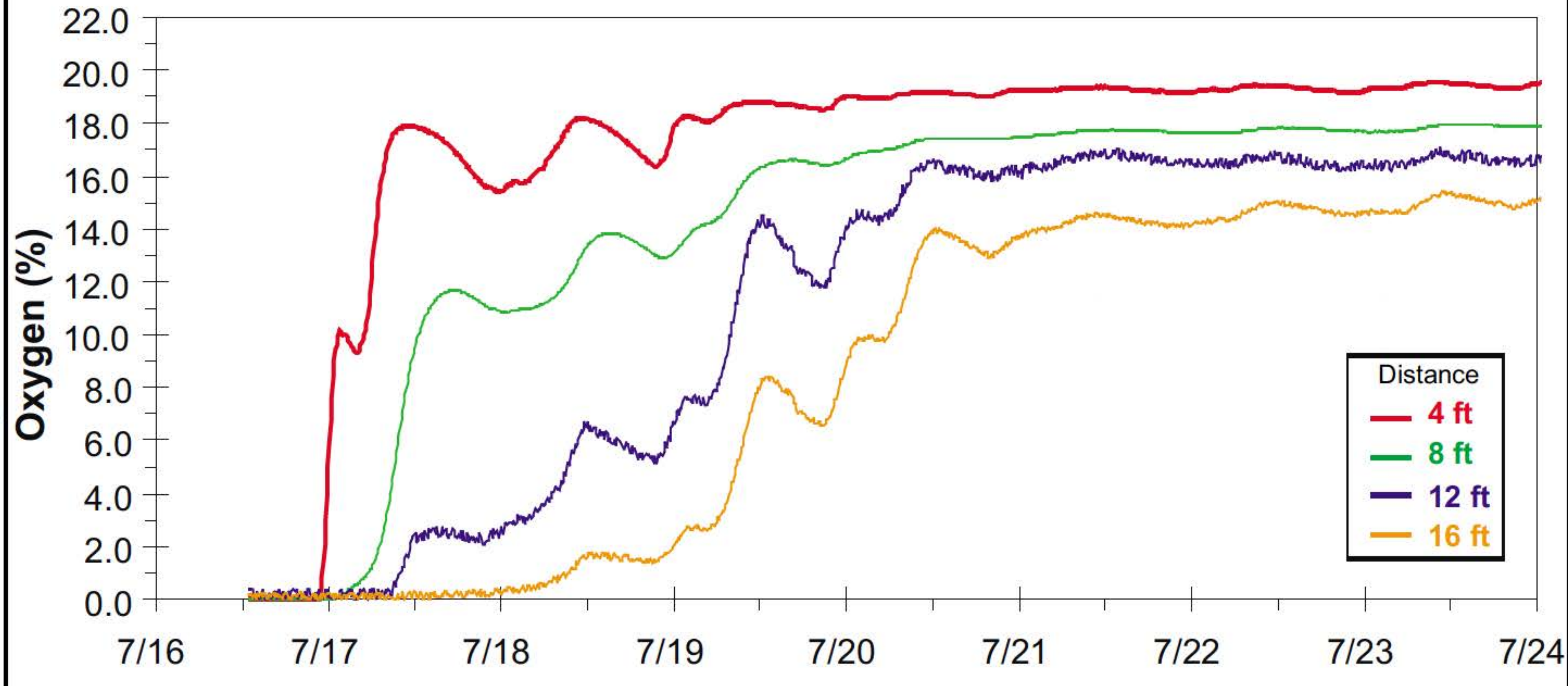

FIGURE 16

OXYGEN RESPONSE AT 30 FEET BGS DURING TEST 4

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Castle Airport, California

\731272\REPORT\FINAL\GRAPHICS\FIGS_L8B.CDR 9/29/00

Oxygen concentrations were also sustained at greater than 15% at 60 feet bgs along one of the VMP arms (PFFABOS02 through PFFABOS08), but remained near 0% at a distance greater than 8 feet from the VW along the other arm (PFFABOS01 through PFFABOS07). The most likely explanation for this result is that the 60-foot deep VMP screens were within the capillary fringe and air movement at this depth was restricted by lower air-filled porosities. This explanation is supported by the sometimes erratic differential pressure measurements (fluctuations between the maximum and minimum transducer range) which occurred at these same depths.

Similar to the results from Test 2, the Test 4 results were a positive indication that air flow rates could significantly increase and sustain oxygen concentrations at significant distances from the VW. In order to better estimate the long-term radius of influence from use of the passive valve, Test 4 was continued for seven weeks. Oxygen measurements were then taken at PFFAVMP15, located at 41.5 feet from the VW (Figure 6), following seven weeks of air injection using the passive valve. Oxygen concentrations in PFFAVMP15 at 42 feet bgs increased from 0% at the start of Test 4 to 5.5% at the end of Test 4. Since 5% is typically the oxygen concentration used to indicate that microbial activity is not oxygen limited, this result provides some evidence that a short-term passive bioventing radius of influence is approximately 42 feet at the site.

5.2.5 Tests 5 and 6. At the end of Test 4, an analysis of the data from Test 2 (Section 5.2.2) indicated that a repeat of the configuration used in Test 2 was needed due to weather-related barometric pressure changes. Therefore, Tests 5 and 6 were conducted, which were essentially a repeat of the same conditions of Test 1/Test 3 (VW remained closed) and Test 2 (VW open without the passive valve installed). As during Test 3, oxygen concentrations during Test 5 decreased to 0% within a few weeks. Respiration rates ranged from 0.38% O_2/day to 0.88% O_2/day during Test 5. These respiration rates were somewhat lower, but more consistent from location to location, during this second respiration test compared to Test 2, probably indicating that some reductions in the most biodegradable contaminants occurred during the extended period of air injection during Test 4 and that biomass increases were more consistent from location to location.

A plot of air flow due to changes in barometric pressure during Test 6 is shown on Figure 17. Barometric pressure change was mostly due to diurnal effects rather than weather-front related (compare to Figure 11). Therefore, oxygen response for Test 6 is reflective of that due to regular diurnal changes rather than weather-front related events.

A plot of oxygen concentrations during Test 6 at 30 feet bgs is shown on Figure 18. Although oxygen concentrations increase at all locations at some point during the test period, oxygen concentrations are only sustained above 5% within 8 feet of the VW. Significant fluctuations in oxygen concentration also occur at all locations as the net influx of air is substantially lower without the passive valve. The fluctuations are caused by respiration as well as the reversal of air flow which occurs during decreasing barometric pressure. The air flow reversal causes previously injected air to move back toward the VW and brings in oxygen-depleted air from outside the treatment area. When compared to the oxygen response with the passive valve

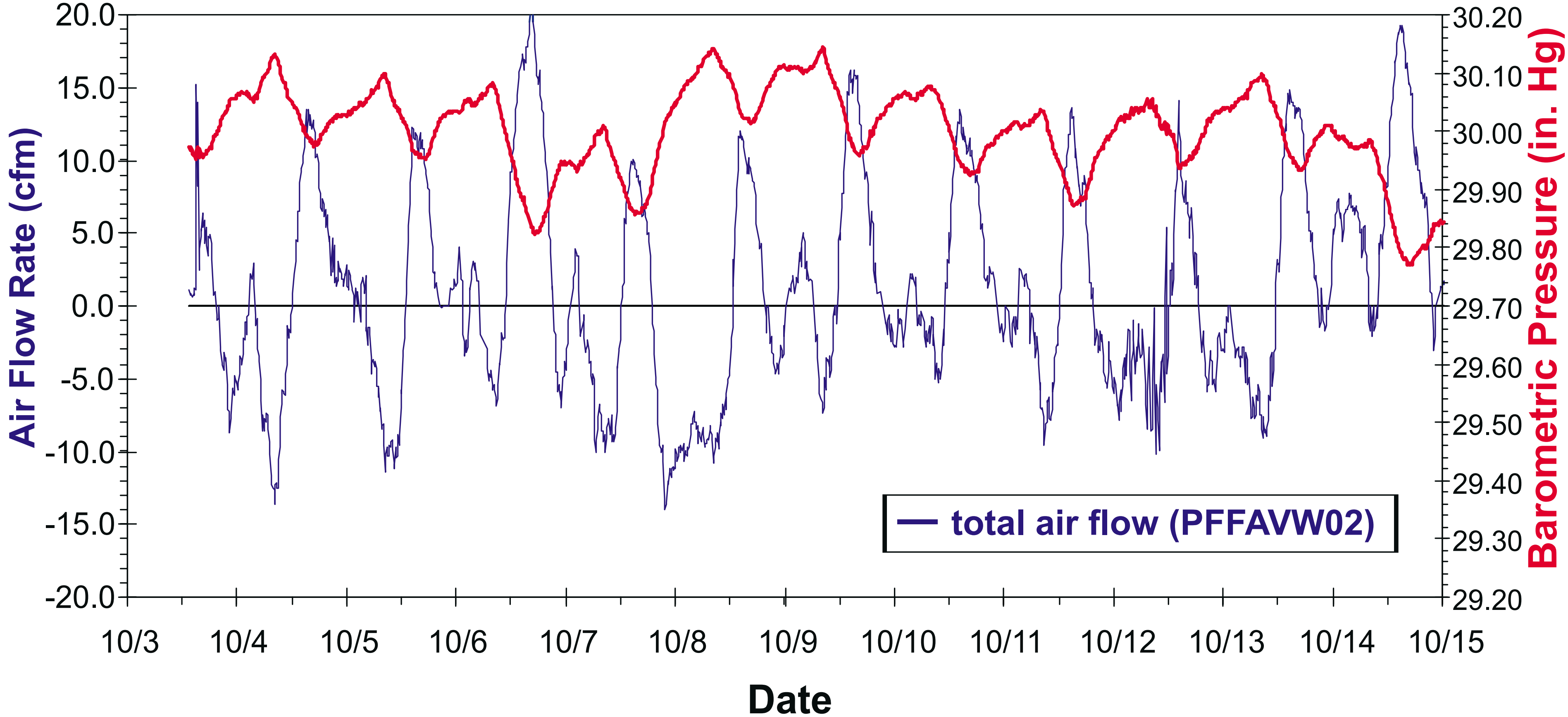

FIGURE 17

AIR FLOW vs. BAROMETRIC PRESSURE DURING TEST 6

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Castle Airport, California

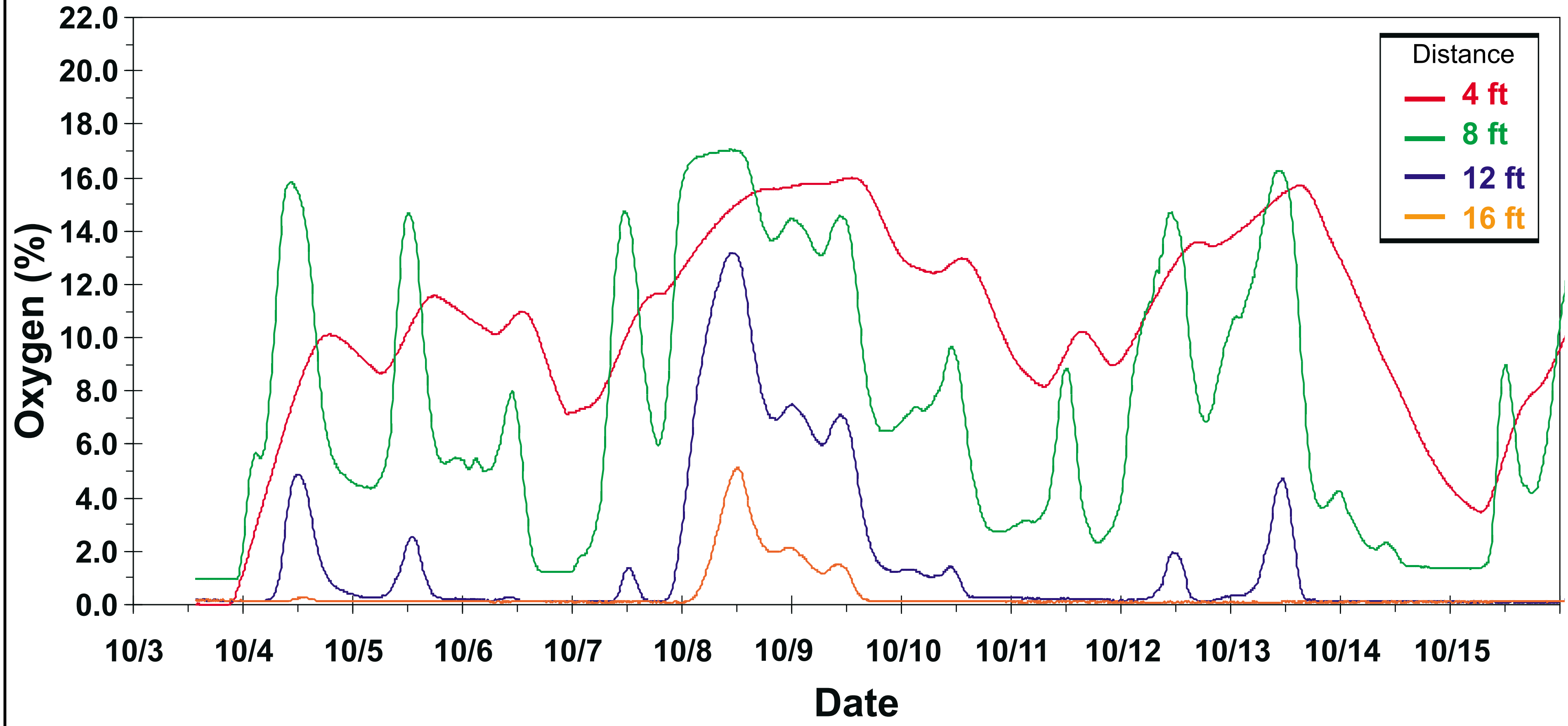

FIGURE 18

OXYGEN RESPONSE AT 30 FEET BGS DURING TEST 6

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Castle Airport, California

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installed during Test 4 (Figure 16), this result clearly indicates the benefit of the passive valve in increasing the radius of influence.

5.2.6 Performance Objectives and Technology Validation. The two performance objectives for the demonstration were: 1) achieving an economical radius of influence, and 2) achieving sufficient air flow rates to meet biological demand (Sections 2.1.5 and 4.1). A discussion of how the demonstration results met the first performance objective, achieving an economical radius of influence, is included in Section 6 (Cost Assessment). A discussion of how the demonstration results met the second objective, achieving air flow rates to meet biological oxygen demand, is partially demonstrated by the increase in oxygen concentrations observed during Test 4 and discussed in Section 5.2.4.

However, both predictions and the associated means of validation also are important to the success of the demonstration. They reflect a transition from previous studies and site characterization data into a successful field demonstration and determine the applicability of the technology at future sites. As discussed in Section 1.3, one of the demonstration objectives is to gather data to support technology implementation and cost assessment at future sites. Comparison of results from this demonstration against predictions comprise the validation plan for this demonstration. If successful, the same prediction methodology could be used at future sites to determine feasibility without time consuming and expensive testing.

The validation plan for this demonstration was to evaluate whether Equation (1) presented in Section 2.3 used for estimating the required air flow rate necessary to meet the maximum oxygen demand can also be used to predict the radius of influence from easily measurable site data. Instead of solving for the required air flow rate (Q) necessary to achieve a pre-determined radius of influence (R_i), Equation (1) can be rearranged and used with measured air flow rates to solve for the radius of influence, R_i, that can be achieved at those measured air flow rates (see Appendix H):

$$R_i = \sqrt{\frac{Q \bullet (C_{max} - C_{min})}{\pi \bullet h \bullet k_o \bullet \theta_a}} \qquad (2)$$

where:

R_i	=	radius of influence [feet]
k_o	=	oxygen-utilization rate (*in situ* respiration rate) [%/day]
Q	=	volumetric air flow rate [cubic feet per day (cfd)]
θ_a	=	air-filled porosity [volume air/volume soil]
h	=	soil thickness through which air flows [feet]
C_{max}	=	oxygen concentration of background/injected air [%] (typically 20.9%)
C_{min}	=	minimum oxygen concentration for aerobic conditions [%] (typically 5.0%)

Since it is simpler and less expensive to conduct short-term air flow testing at one VW or MW than to measure an unknown, long-term radius of influence using multiple VMPs, validation and prediction using Equation (2) would result in a powerful and cost-effective screening tool for future sites.

The data from Tests 2 and 4 and the associated measured and predicted radius of influence based on Equation (2) for Tests 2 and 4 are provided in Table 6. The air flow used in the equation was the net total air flow into the VW during the tests (*i.e.,* the total air flow into the VW minus the total air flow out of the VW). For the ISR rate, the average ISR rate measured during Test 2 was used. For the thickness of the aerated vadose zone, the length of vadose zone between the bottom of the upper confining layer at 25 feet bgs and the depth to groundwater (60 feet) was used. Air-filled porosity was calculated from the average soil moisture (Table 2) and an estimated total soil porosity of 0.35 (based on site lithologic data) using the calculations provided in the bioventing protocol documents. The methodology could not be used for the data collected during Test 6 because the net air flow during Test 6 was out of the well except during the initial few days of the test.

Table 6
Comparison of Measured vs. Predicted Radius of Influence

Test Number	h, Vadose Zone Thickness (ft)	k_o, Average Oxygen-utilization Rate (%/day)	Length of Test (days)	θ_a Calculated Air-filled Porosity (-)	Q Net Total Air Flow Into VW (cf)	Predicted R_i (ft)	Measured R_i (ft)
Test 2	35	1.0	16	0.27	24,900	29	>16
Test 4	35	1.0	52	0.27	175,000	42	42

The results indicate that Equation (2) was successful in predicting the measured radius of influence. Therefore, use of this equation in combination with ISR data, site lithologic information, soil moisture data, and air flow rates can be used as a screening tool at future sites. Site lithologic information and soil moisture data are readily available at most sites. ISR tests are usually performed at any site undergoing an evaluation of either conventional bioventing or passive bioventing and are inexpensive to conduct. The parameter which is typically not available at potential passive bioventing sites is air flow. However, air flow measurements from an existing or newly constructed VW are also relatively inexpensive to collect, requiring only off-the-shelf components as used during this demonstration (Appendix F). Such testing could be conducted over a period of only a few weeks to determine feasibility and to estimate a radius of influence. If the estimate of a radius of influence is sufficient to make passive bioventing an economic alternative, then additional longer-term or more thorough testing could be conducted.

To evaluate the sensitivity of the predicted radius of influence to soil moisture, the range of moisture contents from the more permeable zones through which air is flowing (see Section 2.3 and Table 2) was used to calculate a range of air-filled porosities using the procedure in Section 1.4 of Volume II from USEPA ORD, 1995. The calculation resulted in a range of air-filled porosity of between 0.20 to 0.33. Air flow data collected during Test 4 was then used

in Equation (2) to calculate a range of predicted radii of influence of between 38 and 49 feet, compared to the 42 feet presented in Table 6. For this site, because soil moisture content is relatively consistent over space for the same lithologic zone, the predicted radius of influence is not particularly sensitive to assumptions used for air-filled porosity. At sites with more variable moisture contents, soil type, or advective air flow regimes, it is recommended that more intensive air flow measurements with depth, more extensive sensitivity analyses, and/or more complex modeling be used to achieve adequate estimates of the predicted radius of influence.

For the Castle site, the more permeable strata were relatively homogeneous as shown on the boring logs included in Appendix C. At other sites, soils may not be relatively homogeneous. Under more heterogeneous conditions, the radius of influence may be larger horizontally but oxygen would not be evenly distributed with depth. In these cases, the predictive model with an appropriate strata thickness should be used to approximate or bound the expected radius of influence. A prudent approach under these conditions would be to start at wider VW spacing based on the bounded radius of influence from the predictive modeling. Vapor monitoring points should also be screened at enough depths and distances to evaluate the oxygen distribution.

A strong correlation between subsurface differential pressure and air flow also was observed during this demonstration (Figure 19). While a correlation was expected based on Bernoulli's equation, additional short-term testing at other sites would be required to determine whether the same correlation exists at other sites and to determine how site characteristics (*i.e.,* permeability, soil moisture) could be used to predict the correlation factor. If the correlation factor could be predicted with some confidence, then only differential pressure measurements would be required to predict air flow rates and the expected radius of influence from a passive approach. Since it is much simpler to measure differential pressure than to measure air flow, this would allow for very inexpensive feasibility testing.

5.3 Technology Comparison

As discussed in Section 2.2 and 2.3, the most valid technology comparison for passive bioventing is to conventional bioventing. Given the similarities between the two technologies and the cost-effectiveness of conventional bioventing, passive bioventing would likely only be considered as an alternative to conventional bioventing rather than compared against other technologies.

The radius of influence from passive bioventing and conventional bioventing is the parameter for evaluating the success of each technology and comparing the two technologies. As discussed in Section 3.2.6, air permeability testing and oxygen influence testing during conventional bioventing pilots tests conducted at the demonstration site indicated that a radius of influence of 110 feet could be expected in the deeper vadose zone soils (those below 25 feet bgs). As discussed in Section 5.2.4, the measured radius of influence from the passive bioventing demonstration was approximately 42 feet.

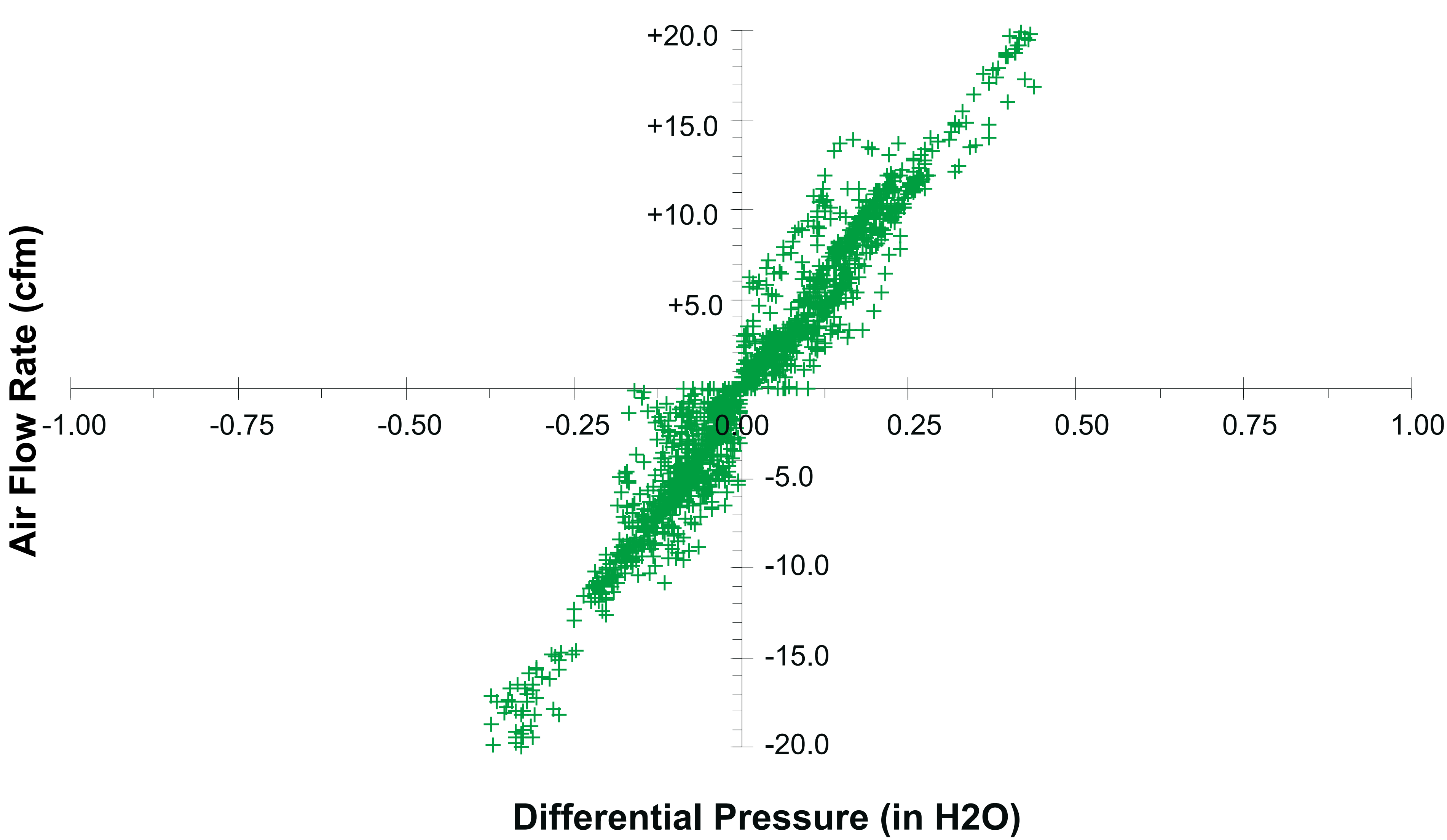

FIGURE 19

AIR FLOW vs. SUBSURFACE PRESSURE DURING TEST 4

PFFA
Castle Airport, California

\731272\REPORT\FINAL\GRAPHICS\FIGS_L8B.CDR 9/29/00

As expected, the passive bioventing radius of influence is significantly smaller than the conventional bioventing radius of influence. However, as discussed in Section 2.3 it is expected that the radius of influence from a passive bioventing system would approach that of a conventional bioventing system over a relatively long time period (on the order of several months, much longer than the period of testing during this demonstration). Although initially the radius of influence will be limited by the microbial demand near the VW, as areas near the VW are remediated and the oxygen demand is satisfied, the radius of influence would expand (*i.e.,* the oxygen-utilization rate would decrease from that shown in Table 6).

For example, if the oxygen-utilization rate dropped from 1.0% O_2/day to 0.25% O_2/day at the PFFA site, the predicted radius of influence would be 85 feet (rather than 42 feet) compared to the conventional bioventing radius of influence of 110 feet (which is primarily limited by induced pressure differences from the blower and vertical air flow components rather than oxygen-utilization rate). A passive bioventing VW design which relied upon this long term radius of influence based on decreasing oxygen-utilization rates would not require a significantly greater number of wells than a conventional bioventing system (approximately 1.5 times as many VWs for the same areal coverage). Results from the AFCEE Bioventing Pilot Test Initiative indicate that decreases in oxygen-utilization rates of this order of magnitude could be expected within 6 months to a year of bioventing. While the expansion of the radius of influence may come at the cost of longer remediation times, the time/cost tradeoff may be acceptable at some sites. More detailed cost comparisons between passive and conventional bioventing are provided in Section 6.

While the estimated radius of influence under declining biodegradation rates can be easily estimated using Equation (2), there are currently no available models, equations, or calculations which can predict the long-term radius of influence based only on soil permeability and the quickly changing and relatively low pressure differentials which occur in passive bioventing. Measuring air flow and oxygen increases with distance and then using Equation (2) to perform sensitivity analysis on the predicted radius of influence under declining biodegradation rates, as described in this section, is likely to be a better approach. The predicted radius of influence using actual air flow rates, biodegradation rates, and soil moisture at a site can then be used to appropriately space the VW and VMP network.

6. Cost Assessment

6.1 Cost Performance

The information included in this section provides an assessment of the expected operational costs for passive bioventing when implemented, not the demonstration costs. For comparison purposes, the expected costs are given for a single site of approximately the same size as the PFFA demonstration area, approximately 115,000 square feet (ft^2) or 2.6 acres.

Using the second level work breakdown structure (WBS) coding system detailed in the *Guide to Documenting Cost and Performance for Remediation Projects* (USEPA, 1995), costs for a typical passive and conventional bioventing system for a site of similar size to the demonstration area were estimated. These costs are shown in Table 7 and detailed in Appendix G.

Costs were estimated using the *Bioventing Cost Estimator (BVCE) and User's Guide* (NFESC, 1996), experience from the Bioventing Pilot Test Initiative (Downey *et al.*, 1994), and actual costs incurred during both conventional bioventing pilot testing and demonstration test activities at the PFFA at Castle Airport. The costs include the following activities:

- Data review
- Site visits/planning
- Work plan and report preparation
- Regulatory approval
- Equipment costs
- Initial soil vapor survey
- Pilot testing
- Analytical sampling costs
- Well installation
- Full-scale system installation
- Yearly O&M
- System abandonment

6.2 Cost Performance to Conventional and Other Technologies

For comparison, costs are included in Table 7 for both a conventional bioventing system and a passive bioventing system for the same site. The conventional bioventing system design for the area required 3 VWs, 5 VMPs (3 for the pilot test and 2 additional ones for the full-scale system), and one blower system. An upgrade to the existing electrical system (*e.g.,* new distribution panels and meters) was required for the blower system; however, electrical power itself was already at the site (*i.e.,* the PFFA was not a "remote" site). Trenching and asphalt surface repair for the header pipes to the VWs was also required for the conventional system design.

While the passive bioventing system did not require the blower, electrical system upgrade, or trenching and surface repair, the passive system required 6 VWs instead of the 3 VW-design for the conventional system. The passive design was based on the long-term radius of influence estimate of 85 feet (detailed in Section 5.3) as compared to the 110-foot radius of influence for the conventional system. It was assumed that the number of VMPs would remain the same for both systems since the area treated was the same size. Passive valves were needed for the passive system but not the conventional system; however, the valves are not major cost items.

For O&M purposes, the time period from initial installation to closure sampling was estimated at 3 years for the conventional system based on experience gained during the AFCEE Bioventing Initiative. The time period for remediation for the passive system was estimated at 4 years due to the lower air flow rates. Included in the O&M costs were yearly ISR tests. It was assumed that all other costs (*e.g.,* work plans, administration, regulatory oversight) remained the same for both systems.

As shown on Table 7, a passive bioventing system for this site is very cost-competitive with the conventional bioventing system design. The total cost (approximately $283,000) and unit cost (approximately $1.90 per cubic yard) are somewhat lower for the passive system even though it

TABLE 7
Cost Comparison
Passive Bioventing vs. Conventional Bioventing

WBS	Description	Unit Cost ($)	Units	Passive Bioventing Units	Passive Bioventing Cost ($)	Conventional Bioventing Units	Conventional Bioventing Cost ($)	Cost Basis
BEFORE TREATMENT COST ELEMENTS								
33-01	Mobilization and Preparatory Work							
	Design costs	28,400	each	1	28,400	1	28,400	NFESC, 1996
	Health and Safety Plan	10,000	each	1	10,000	1	10,000	NFESC, 1996
	Pilot-Scale Work Plan	10,000	each	1	10,000	1	10,000	NFESC, 1996
	Full-Scale Remedial Action Work Plan	25,000	each	1	25,000	1	25,000	NFESC, 1996
	Quality Assurance Plan	10,000	each	1	10,000	1	10,000	NFESC, 1996
	SUBTOTAL				**$ 83,400**		**$ 83,400**	
33-02	Monitoring, Sampling, Testing, and Analysis							
	Fixed sampling and testing equipment	7,870	each	1	7,870	1	7,870	NFESC, 1996
	Soil gas survey	8,635	each	1	8,635	1	8,635	Gregg Drilling
	Pilot testing (incl. drilling but not analytical costs)	25,949	each	1	25,949	1	25,949	NFESC, 1996
	Soil analysis (during pilot & full-scale install)	104	sample	35	3,649	35	3,649	NFESC, 1996
	Soil vapor analysis (during pilot & full-scale install	130	sample	14	1,820	14	1,820	NFESC, 1996
	SUBTOTAL				**$ 47,923**		**$ 47,923**	
33-03	Site Work							
	Trenching	16	foot	0	-	850	13,600	Marcor
	Electrical Utilities	3,000	total	0	-	1	3,000	Atwater Electric
	SUBTOTAL				**$ -**		**$ 16,600**	

TABLE 7 (continued)
Cost Comparison
Passive Bioventing vs. Conventional Bioventing

WBS	Description	Unit Cost ($)	Units	Passive Bioventing Units	Passive Bioventing Cost ($)	Conventional Bioventing Units	Conventional Bioventing Cost ($)	Cost Basis
TREATMENT COST ELEMENTS								
33-11	Biological Treatment							
	Operations & maintenance (passive)	1,998	yr	4	7,992	0	-	NFESC, 1996
	Operations & maintenance (conventional)	11,113	yr	0	-	3	33,339	NFESC, 1996
	Follow-up respiration testing	4,569	yr	2	9,138	2	9,138	NFESC, 1996
	Passive valves	149	each	6	894	0	-	Nisei/Ryan Herco
	Field instrument rental	1,760	total	1	1,760	1	1,760	Hazco
	Blower system	4,162	each	0	-	1	4,162	NFESC, 1996
	VW installation (full-scale, but not pilot test)	5,946	each	5	29,730	2	11,892	NFESC, 1996
	VMP installation (full-sacle, but not pilot test)	5,720	each	2	11,440	2	11,440	NFESC, 1996
	SUBTOTAL				**$ 60,954**		**$ 71,731**	
AFTER TREATMENT COST ELEMENTS								
33-21	Demobilization							
	Well abandonment	17	foot	715	12,155	520	8,840	Gregg Drilling
	Closure soil sampling	75	sample	18	1,350	18	1,350	NFESC, 1996
	Closure soil vapor sampling	130	sample	9	1,170	9	1,170	NFESC, 1996
	Final Report	50,000	each	1	50,000	1	50,000	NFESC, 1996
	SUBTOTAL				**$ 64,675**		**$ 61,360**	
33-9X	Other Costs							
	Contingency	26,200	each	1	26,200	1	26,200	NFESC, 1996
	SUBTOTAL				**$ 26,200**		**$ 26,200**	
TOTAL COST					**$ 283,152**		**$ 307,214**	
COST PER CUBIC YARD TREATED					**$ 1.93**		**$ 2.09**	

required twice as many VWs to cover the same area. This estimate shows that with an adequate radius of influence, the cost to install more VWs with a passive system can be more than offset by the costs to install a blower, electrical power, and trenching and piping and to operate and maintain a conventional bioventing blower system. The yearly power costs alone for the blower are approximately $5,000, while the cost to install the trenching and piping at such a large, asphalted site with many subsurface utilities was approximately $14,000. These savings along with other yearly O&M savings more than make up for the costs to install additional VWs and operate the system for a longer period of time.

While the costs are lower, the time period for remediation with the passive system is longer (4 years compared to 3 years) which may not be acceptable at some sites. This time period extension was primarily needed due to the use of a design radius of influence based on declining respiration rates, as discussed in Section 5.3. For comparison, if the time period for remediation is kept identical with both systems and a design radius of influence of 42 feet is used for the passive system (the demonstrated radius of influence after only seven weeks), the cost of installing the passive bioventing system would increase by approximately $21,000 due to the need for 9 VWs instead of 6. O&M costs would decrease somewhat (approximately $2,000) due to the need for fewer yearly ISR tests. Using these assumptions, the cost of the passive system would then be only $5,000 lower than for the conventional system.

The reduction in cost if conventional bioventing takes only 2 years instead of 3 years is $11,113 (Table 7, Operations & Maintenance costs for conventional system). This amount is still less than the total cost differential between the 2 options ($24,062 as shown in Table 7) using the 85-foot radius of influence estimate. However, it is greater than the total cost differential if the conservative 42-foot radius of influence is used ($5,000). Therefore, if the conventional system is operated for only 2 years and a conservative 42-foot radius of influence is used, then a conventional approach is more cost effective than a passive approach. However, a passive system designed using the conservative 42-foot radius of influence estimate might also need to be operational for a reduced period of time, offsetting some of this cost differential.

Clearly, the time for operating the conventional system and the estimate for a long-term radius of influence are the most cost-sensitive parameters for the Castle site. A similar cost comparison should be done for any site which evaluates the magnitude of the total cost differential against other fixed or recurring costs of a similar magnitude (*e.g.,* yearly O&M costs). In addition, sensitivity analysis should be performed on those parameters which significantly affect the total cost (*e.g.,* radius of influence estimate). It is important to emphasize that sites other than Castle may have significantly different sensitivities to cost, although the radius of influence estimate is likely to be the most sensitive for almost all sites because it affects well spacing and capital costs for well installation.

In general, the point at which the cost to install any additional VWs under a passive bioventing approach offsets the blower capital and O&M costs under a conventional bioventing approach will be site-specific and dependent upon:

- differences in the radius of influence between conventional and passive bioventing;
- cost to install electric power;
- local utility costs;
- drilling costs (affected primarily by contamination depth, soil type, and location); and,
- the time frame needed to achieve remedial goals.

The most difficult factor listed above to currently predict is the difference in radius of influence between conventional bioventing and passive bioventing. An empirical relationship was developed as part of the U.S. Air Force Bioventing Initiative to relate pressure response from a short one-day air permeability test to radius of influence for conventional bioventing design purposes (see Section 1.5 of Volume II from USEPA ORD, 1995). Site cleanup times are also difficult to predict, even with conventional bioventing, but are primarily a function of the microbial respiration rate, achievable air flow, contaminant concentrations, and soil porosity (see Section 1.4 and Section 3 of Volume II from USEPA ORD, 1995). Therefore, simple inexpensive tests (air permeability and *in situ* respiration tests) are already available to predict the conventional radius of influence and monitor site cleanup progress.

The only factor remaining is the radius of influence for the passive system. As discussed in Section 5.2.6, the demonstration data supports the use of short-term natural air flow measurements and a recasting of Equation (1) as presented in Section 2.2 of Volume II from USEPA ORD, 1995 (where it is used to size blower systems) to determine a radius of influence for a passive system. The demonstration study's validation of this equation to predict the radius of influence, and therefore estimated costs, for a passive bioventing system is a significant success. Therefore, using relatively inexpensive, short-term air flow measurements alone, a cost comparison between passive and conventional bioventing can now be conducted with some confidence.

At sites where nutrients are limiting biodegradation rates or can be shown to significantly decrease cleanup time, a passive approach might be less cost effective due to the inability to add nutrients under a passive approach. However, the USEPA ORD protocol concludes, based on previous studies, that nutrients are generally not limiting biodegradation at most sites. An equation is provided in the protocol for comparing microbial nutrient requirements with available nitrogen and phosphorus in site soils. Data from the Castle soils (on the order of 30 to 60 mg/kg nitrogen and 200 mg/kg phosphorus) were compared with the nutrient requirements from the protocol (10 mg/kg nitrogen and 1 mg/kg phosphorus) which confirmed that nutrients are unlikely to be rate limiting at Castle.

7. Regulatory Issues

7.1 Approach to Regulatory Compliance and Acceptance

For the passive bioventing demonstrations at the PFFA, the lead regulatory agency was the State of California Regional Water Quality Control Board (RWQCB), Central Valley Region. Other

regulatory agencies providing secondary oversight due to their responsibilities for the Castle Airport facility were the U.S. Environmental Protection Agency (USEPA) and the State of California Department of Toxic Substances Control (DTSC).

The regulators were kept informed of demonstration test activities through periodic presentations made at the monthly Remedial Project Managers (RPM) meetings conducted by the Air Force Base Conversion Agency (AFBCA) located at Castle Airport. The regulators were supportive of the demonstration activities as a complement to ongoing conventional bioventing testing and implementation. There were no significant regulatory obstacles or impacts on schedule due to regulatory review.

Although a residential advisory board (RAB) is in place at Castle Airport and holds regular monthly meetings coinciding with the regular RPM meetings, to date there has not been any public participation or involvement in the demonstration. This is primarily due to the limited time of members of the RAB and their priorities for other sites at the Castle Airport facility.

8. Technology Implementation

8.1 DoD Need

The most recent USEPA estimates of the number of DoD sites that may have POL contamination in soil requiring cleanup is approximately 2,000 sites (USEPA, 1997). This total number of sites is based on the number of site types that would be expected to have predominantly POL contamination (*i.e.,* USTs, fire/crash training areas, ASTs, POL distribution lines, oil/water separators, maintenance yards, and washracks). Assuming that at least half of these sites could benefit from a passive approach (either exclusively or as a longer-term, follow-up technology to either SVE or conventional bioventing), a total savings of approximately $25 million could be realized based on an average per site savings of $25,000. Not included in this estimate is the cost for remote sites, which while relatively fewer in number could require costs in excess of $100,000 each just to bring in the required electrical power. If it is assumed that even 5% of the applicable sites require such a significant power expense, then an additional savings of $10 million savings ($35 million total) could be realized.

The estimate given above is also conservative because it does not include the number of sites with chlorinated solvent contamination in soil which might benefit from passive soil vapor extraction, a companion technology which is based on the same principles and for which much higher treatment costs, and hence cost savings, could be realized.

8.2 Transition

In order to continue the transition and implementation of passive bioventing, the following steps are recommended:

1) Longer-term radius of influence testing. Although results from this demonstration clearly indicated the validity of using existing equations for predicting a radius of influence for passive bioventing in the short-term (*i.e.,* on the order of weeks), more extensive testing is needed to determine whether the radius of influence from passive bioventing can approach a conventional bioventing radius of influence over the long term (*i.e.,* on the order of months or years).

2) Additional short-term demonstrations to verify technology application. Although results from this demonstration clearly indicated that the technology is applicable under shallow groundwater and stratified-soil conditions, all of the previous passive bioventing demonstrations have been conducted in the western U.S. It is recommended that additional short-term demonstrations be conducted in the eastern and midwestern U.S., where site characteristics are potentially quite different (*e.g.,* soil moisture and type, barometric pressure changes). Since air flow and subsurface differential pressure have been shown to be good predictors of radius of influence, these short-term tests could be conducted very inexpensively using existing VWs or MWs and portable remote monitoring equipment.

3) Technology Transfer. The success of the demonstration and techniques which can be used to predict a passive bioventing radius of influence need to continue to be transferred to DoD, DOE, and private industry. The previously-submitted user data package is expected to significantly assist with this technology transfer.

   In addition to the user data package, as of the date of this report results from the demonstration have been presented at four conferences (Third Tri-Service Environmental Technology Workshop, August 1998; Partners in Environmental Technology, December 1998; Water Environment Federation's WEFTECH '99, October 1999; National Ground Water Association's Petroleum Hydrocarbons Conference, November, 1999). Papers were submitted for publication in the proceedings for these conferences, one of which is available on the internet (http://aec-www.apgea.army.mil/prod/usaec/et/etw/07.htm).

   An article was also published in the Summer 1998 edition of NFESC's Remedial Project Manager's newsletter *RPM News*. The Naval Facilities Engineering Command has recently published a TechData Sheet (NAVFAC, 2000). Presentation and discussion of results are also planned in the future at additional meetings, conferences, and teleconferences of the Alternative Restoration Technology Team (ARTT), the Tri-Service Environmental Working Group, the Clean-up Review Tiger Team, and the Installation Restoration Program.

All of the above actions are planned for implementation in 2000/2001 by the points of contact provided in Appendix A.

9. Lessons Learned

The following lessons were learned during implementation of this demonstration:

1) Difficulty of site selection. Site selection for this demonstration was a time-consuming process. Reasons for this included:

   a) Initially focusing on sites which appeared to have very limited application of the technology (*i.e.,* tidally-influenced sites).
   b) Limited information was often available to adequately screen sites with a degree of confidence that the site would meet the demonstration objectives (*i.e.,* have adequate air flow). Therefore, additional time was spent visiting multiple candidate sites and collecting pre-demonstration data (*e.g.,* air flow).

   The authors wish to emphasize the importance of partnering for demonstrations. Partnering can help to overcome site selection difficulties by providing access to personnel and resources which would otherwise be unavailable.

   Another, but nevertheless important, factor which made site selection difficult was that petroleum sites are now often considered "low priority" sites or often have undergone some degree of remediation. Notably, in contrast to this deficiency as a demonstration site characteristic, these sites could be excellent candidates for sites where conventional systems could be turned off in favor of long-term operation in a passive mode.

2. Radius of influence estimate and long-term radius of influence. Equation (2) presented in Section 5.2.6 was successful in predicting a short-term radius of influence based on air flow measurements, ISR test data, and soil moisture and soil porosity data. However, depending on the time frame required to reach site cleanup, well spacing may be better based on the expected long-term radius of influence under declining biodegradation rates. Additional demonstrations should be run over a longer period of time to determine if the radius of influence for a passive system approaches that measured by a conventional bioventing pilot test.

3. Correlation of air flow to subsurface differential pressure. As shown on Figure 19, there was a strong correlation between air flow and subsurface differential pressure at the PFFA site. Additional short-term testing at other sites should be done to determine whether the same correlation exists at other sites and to determine how site characteristics (*i.e.,* permeability, soil moisture) could be used to predict the correlation factor. If the correlation factor could be predicted with some confidence, then only differential pressure measurements would be required to predict air flow rates and the expected radius of influence from a passive approach. Since it is much simpler to measure differential pressure than to measure air flow, this would allow for very inexpensive feasibility testing.

4. Passive valve construction. As discussed in Section 4.2.5, the passive valve originally was constructed using single-cell foam rubber for the internal seal and it did not perform as well as mylar. If the design shown on Figure 4 is used, mylar should be used for the seal. In addition, users should note that a passive valve called the "BaroBall", developed by Savannah River Site researchers, is now commercially available (Durham Geo-Enterprises, Stone Mountain, GA, 770-465-7557). The BaroBall valve was not evaluated or used during this demonstration.

5. Oxygen sensors. The directly-buried oxygen sensors provided good quality data and were relatively simple to install using standard hollow-stem auger techniques. It is strongly recommended that the sensors with the integrated pressure measurement and sampling port (as used during this demonstration) also be used for any future installations since it allows for soil vapor samples to be collected. These oxygen sensors may also be very cost-competitive at conventional bioventing sites because, with the use of a data logger, ISR tests can be performed unattended.

6. Verticality of boreholes. The verticality measurements indicated that deviations of as much as 1 to 2 feet could be expected at borehole depths of 50 to 60 feet bgs using hollow stem auger techniques. This information should be used to determine if verticality measurements are required at sites where precise radius of influence measurements are needed.

7. Relative humidity. Relative humidity measurements were not collected during this demonstration. It should be added to the list of measured parameters for future passive bioventing demonstrations so that the relationship between relative humidity, ambient temperature, and barometric pressure changes can be evaluated.

8. Reduced iron and ORP. Although the reduced iron and ORP measurements were of some use during the demonstration, since these are measurements not typically collected at bioventing sites, there is not a large data set against which to compare the results. The data collected during this demonstration indicated that despite very anaerobic conditions, the potential for significantly reduced iron or highly reduced soils to exert a significant oxygen demand was relatively low.

10. References

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Appendix A
Points of Contact

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Appendix B
Data Archiving and Demonstration Plan(s)

Electronic data from the demonstration have been included in Appendix D, including data from the testing as well as an electronic version of this report.

A copy of the technology demonstration plans and all other supporting material can be obtained by contacting either the principal investigator or the external contractor point of contact listed in Appendix A. To prevent problems associated with personnel changes, a copy of all demonstration plans, this report, and all electronic data in Appendix D will also be archived in the NFESC Technical Library and in the internal file archive of the external contractor (Parsons). These file archives are specifically designed and administered to allow access to project materials in the event of personnel changes. The Parsons archive will also contain all other project supporting material (*e.g.,* field notebooks, correspondence, subcontractor data). The reference number (also called the job number) for the internal file archive at Parsons is 731272.

Appendix C
Boring Logs, Well Construction Details, Cone Penetrometer Logs, and Borehole Verticality Survey

[Appendix C is only available in the hard copy form of the report]

Appendix D
Electronic Data Summary

Included in this Appendix is a CD-ROM (IBM format) which contains electronic data files for the demonstration. The following files can be found on the CD-ROM:

Name	Description	File Format
F_PB_Rpt.pdf	Final Report (this document)	PDF (Adobe Acrobat)
TESTS.XLS	Data from Tests 1 through 6	Microsoft Excel 97

Files in the PDF (Portable Document Format) are viewable and printable with the free Adobe Acrobat Reader software commonly used for publishing documents on the internet. This software is downloadable from the Adobe Corporation home page at http://www.adobe.com/. Links within the `FReport.pdf` file can be used to automatically open and view individual PDF files or internet links.

Appendices C and F are only available in the hard copy form of the report.

The Microsoft Excel file containing the data downloaded from the data acquisition system (TESTS.XLS) is quite large (over 40 MB). Depending on their computing power and capacity, users wishing to manipulate or view this data may need to divide the file into parts to facilitate analysis.

Appendix E
Photo Documentation

Photo 1. Decontamination of drilling equipment.

Photo 2. Setup of drill rig.

Photo 3. Mobilization of support equipment.

Photo 4. Oxygen sensor.

Photo 5. Attachment of sensor to PVC casing.

Photo 6. Installation of sensor through hollow stem auger.

Photo 7. Placement of sand filter pack.

Photo 8. Verticality measurement in VMP.

Photo 9. Oxygen sensor/VMP surface completion.

Photo 10. Site overview showing VW, VMPs, and data acquisition system.

Photo 11. Collection of soil vapor samples.

Photo 12. Oxygen and hydrocarbon field meters.

Photo 13. VW with passive valve and air flow transducer.

Photo 14. Modular data acquisition system.

Appendix F
Equipment Details and Specifications

[Appendix F is only available in the hard copy form of the report]

Appendix G
Cost Estimates

The attached cost estimating sheets were generated using the *Bioventing Cost Estimator (BVCE) and User's Guide* (NFESC, 1996). Some modifications were made to the cost estimating sheets generated by the BVCE with information that was available and specific to Castle Airport (*e.g.,* drilling costs and blower configuration).

Fixed Costs Independent of Site Size

Site Name and Location: PFFA
Project Estimator: M. Phelps
Estimation Date: 1/19/99

Purchase Options:

Valve tag stamps numbers 1/4 in	☑	GasTech 3250X CO_2/O_2	☑
Valve tag stamps letters 1/4 in		GasTech GT105 TPH	☐
Valve tag stamps numbers 1/2 in	☐	Oil/Water interface probe 100 ft	☐
Valve tag stamps letters 1/2 in		Water level probe 300 ft	☐

Fixed Costs Independent of Site Size:

Item	*Unit*	*Unit Cost*	*Number*	*Cost*	*Vendor/source*
Valve tag stamps numbers 1/4 in	ea	$21.70	1	$21.70	Seton
Valve tag stamps numbers 1/2 in	ea	$42.70			Seton
Valve tag stamps letters 1/4 in	ea	$56.20	1	$56.20	Seton
Valve tag stamps letters 1/2 in	ea	$111.80			Seton
GasTech 3250X CO_2/O_2	ea	$3,700.00	1	$3,700.00	Control Analytics
GasTech GT105 TPH	ea	$1,548.75			Control Analytics
HNu purchase	ea	$4,620.00			Hazco
HNu carrying case	ea	$250.00			Hazco
Helium detector	ea	$4,500.00			Mark Products Inc.
Diluter kit OVA purchase	ea	$750.00	1	$750.00	Hazco
Flow meter, K72-05-0171	ea	$135.40	1	$135.40	King Instruments
GasTech GT105 test kit	ea	$126.00	1	$126.00	Control Analytics
HNu calibration kit	ea	$109.80	1	$109.80	Hazco
1/3 HP compressor/vacuum pump	ea	$228.00	4	$912.00	Grainger
Magnehelic gauge 0-0.25 in H2O	ea	$54.00	5	$270.00	Dwyer
Magnehelic gauge 0-0.50 in H2O	ea	$47.00	5	$235.00	Dwyer
Magnehelic gauge 0-2.0 in H2O	ea	$47.00	5	$235.00	Dwyer
Magnehelic gauge 0-10 in H2O	ea	$47.00	5	$235.00	Dwyer
Stop watch	ea	$39.95	5	$199.75	Fisher
Male connector 68PL-4-2	ea	$1.31	30	$39.30	Forberg Scientific
1/4 in tube x 1/8 in MPT connector	ea	$1.52	30	$45.60	Forberg Scientific
Tee swivel 172PL-4-2	ea	$2.48	5	$12.40	Forberg Scientific
Labor & material for Magnehelic	ea	$135.00			Tim Goodrich
Oil/Water interface probe 100 ft	ea	$1,665.00			ORS Env. Equip.
Water level probe 300 ft	ea	$265.00			Forestry Suppliers
Pressure gauge 0-30 psi	ea	$20.00	2	$40.00	Cole-Parmer
Thermocouple readout (Fluke 52)	ea	$199.00	2	$398.00	Grainger
Vacuum gauge (high) 0-30 in H_2O	ea	$192.85			Cole-Parmer
Vacuum gauge (low) 0-10 in H_2O	ea	$192.85			Cole-Parmer
Valve 5-way multiport	ea	$69.30	5	$346.50	Scioto Valve
Total				$7,867.65	

Comments:

For instrument rental costs, see instrumentation assembly.

Other Costs

Example of Other Costs:

Design Costs:	$28,400
Documentation Costs:	
Health and Safety Plan	$10,000
Pilot-scale Work Plan	$10,000
Full-scale Remedial Action work Plan	$25,000
Quality Assurance Program Plan (QAPP) or Contractor Quality Control (CQC) Plan	$10,000
Project Final Report	$50,000
Total Documentation Costs	$105,000
Site Closure (Sampling and Analysis) Costs:	$2,520
Number of Soil Samples Assumed	18
Number of Soil Vapor Samples Assumed	9
Contingency Costs:	$26,200
Total Other Costs	$162,120

Instrumentation and Monitoring Devices

Site Name and Location: PFFA
Project Estimator: M. Phelps
Estimation Date: 1/19/99

Estimated Parameters:

Area to be Biovented, Ac	2.6
Blower 2 HP, cfm	160
Radius of Influence, ft	110
Depth of Contamination, ft	60
Depth of Construction, ft	65
Number of Vent Wells, calculated	3
Number of Soil Gas MPs, calculated	3
Top of Screen (vent well), ft	25
Bottom of Screen (vent well), ft	65
Upper Screen Depth (SG MP), ft	25
Lower Screen Depth (SG MP), ft	55
Borehole Diameter (vent well), in	10
Borehole Diameter (SG MP well), in	8
Drill Rate, ft/hr	8
Soil Sample Spacing, 1/ft	15
Mob/Demob Distance, mi	200
Bulking Factor for Soil, unitless	1.3
Heterogeneity Factor (samples/well)	1
Screen Diameter, in	4
Screen Length, ft, calculated	40
SG MP Screen Interval, ft	15
Bentonite Plug Thickness, ft	5
Instrumentation Total Cost	**$1,760**

User Options:

Rental	☑	HNu rental
		Helium detector
Purchase	☐	HNu purchase
		Helium detector
None	☐	No Purchase

Instrumentation and Monitoring Device Item & Cost:

Item	*Unit*	*Unit Cost*	*Number*	*Cost*	*Vendor/source*
HNu rental	daily	$85.00	6	$510.00	Hazco
Helium detector, rental	weekly	$370.00	2	$740.00	Hazco
OVA Rental	daily	$85.00	6	$510.00	Hazco
Total				$1,760.00	

Comments:

For instrument purchase prices (instead of rental), see FXCOSTS sheet.
Assumed that permeability tests will be performed over a manageable portion of the site.
Helium meter rented for helium tracer test during pilot testing

Soil Gas Survey

Site Name and Location: PFFA
Project Estimator: M. Phelps
Estimation Date: 1/19/99

Estimated Parameters:

Area to be Biovented, Ac	2.6
Blower 2 HP, cfm	160
Radius of Influence, ft	110
Depth of Contamination, ft	60
Depth of Construction, ft	65
Number of Vent Wells, calculated	3
Number of Soil Gas MPs, calculated	3
Top of Screen (vent well), ft	25
Bottom of Screen (vent well), ft	65
Upper Screen Depth (SG MP), ft	25
Lower Screen Depth (SG MP), ft	55
Borehole Diameter (vent well), in	10
Borehole Diameter (SG MP well), in	8
Drill Rate, ft/hr	8
Soil Sample Spacing, 1/ft	15
Mob/Demob Distance, mi	200
Bu king Factor for Soil, unitless	1.3
Heterogeneity Factor (samples/well)	1
Screen Diameter, in	4
Screen Length, ft, calculated	40
SG MP Screen Interval, ft	15
Bentonite Plug Thickness, ft	5
Soil Gas Survey Total Cost	**$8,635**

Soil Gas Survey Item & Cost:

Item	*Unit*	*Unit Cost*	*Number*	*Cost*	*Vendor/source*
Carbon dioxide, size s3 10% bal N_2	ea	$124.00	2.6	$322.40	Scott Specialty Gases
Hexane, size s3 4800 in air	ea	$124.00	2.6	$322.40	Scott Specialty Gases
Oxygen, size s3 10% balance N_2	ea	$124.00	2.6	$322.40	Scott Specialty Gases
Demolition electric hammer	ea	$1,600.00	0	$0.00	KVA Associates
CPT Mob/Demob Rate	mile	$3.00	400	$1,200.00	Greg Drilling
CPT Rate (incl. grouting)	feet	$8.50	180	$1,530.00	Greg Drilling
CPT Soil Vapor Sample Collection	ea	$150.00	12	$1,800.00	Greg Drilling
CPT Soil Sample Collection	ea	$100.00	12	$1,200.00	Greg Drilling
Demolition hammer adaptor	ea	$288.00	0	$0.00	KVA Associates
Intercnctng nipple hollow Ni pltd	ea	$23.00	0	$0.00	KVA Associates
Intercnctng nipple solid S/S	ea	$18.00	0	$0.00	KVA Associates
Latex tubing 3/16 in I.D.	100 ft	$52.58	1	$52.58	NewAge Industries
Nylon tubing 1/4 in (natural)	50 ft pk	$19.25	1	$19.25	Cole-Parmer
Plastic flasks 250 ml	12/case	$6.27	0	$0.00	U.S. Plastics
Soil gas probe shaft section 2.5 ft	ea	$255.00	0	$0.00	KVA Associates
Soil probe jack adptr (special made)	ea	$200.00	0	$0.00	
Tedlar bags	10/box	$82.00	5.2	$426.40	SKC
Utility Jack	ea	$100.25	0	$0.00	Grainger
Well pt slotted intake assy 3 ft	ea	$478.00	0	$0.00	KVA Associates
Labor (1 geo)	hr	$60.00	24	$1,440.00	
Labor (2 techs)	hr	$120.00	0	$0.00	
Soil Gas Survey Total				$8,635.43	

Comments:

Pilot Test

Site Name and Location: PFFA
Project Estimator: M. Phelps
Estimation Date: 1/19/99

Estimated Parameters:

Area to be Biovented, Ac	2.6
Blower 2 HP, cfm	160
Radius of Influence, ft	110
Depth of Contamination, ft	60
Depth of Construction, ft	65
Number of Vent Wells, calculated	3
Number of Soil Gas MPs, calculated	3
Top of Screen (vent well), ft	25
Bottom of Screen (vent well), ft	65
Upper Screen Depth (SG MP), ft	25
Lower Screen Depth (SG MP), ft	55
Borehole Diameter (vent well), in	10
Borehole Diameter (SG MP well), in	8
Drill Rate, ft/hr	8
Soil Sample Spacing, 1/ft	15
Mob/Demob Distance, mi	200
Bulking Factor for Soil, unitless	1.3
Heterogeneity Factor (samples/well)	1
Screen Diameter, in	4
Screen Length, ft, calculated	40
SG MP Screen Interval, ft	15
Bentonite Plug Thickness, ft	5

User Options:

3-1/4 in Environ. soil sampling kit	☑
PVC 2 in sch 40 screen 5 ft	☐
PVC 2 in sch 40 screen 10 ft	☑
PVC 4 in sch 40 screen 5 ft	☐
PVC 4 in sch 40 screen 10 ft	☐
PVC 2 in sch 40 casing 5 ft	☐
PVC 2 in sch 40 casing 10 ft	☑
PVC 4 in sch 40 casing 5 ft	☐
PVC 4 in sch 40 casing 10 ft	☐

Pilot Installation Total	$18,291
Soil Analysis Total	$1,768
Hellium Tracer Test	$1,099
Permeability Test	$2,899
Respiration Test	$4,569
Pilot Test Total Cost	**$28,627**

Pilot Scale Installation:

Item	Unit	Unit Cost	Number	Cost	Vendor/source
Driller Mob/Demob of equipment	mile	$3.00	400	$1,200.00	Gregg Drilling
Driller travel	crew hr	$60.00			Gregg Drilling
Driller Per diem, per crew	crew day	$168.00	1	$168.00	Gregg Drilling
Driller charge rate (labor & equip)	hour	$210.00			Layne Env Services
Driller charge rate (labor & equip)	foot	$30.00	260	$7,800.00	Gregg Drilling
3-1/4 in Environmental soil sampling kit	ea	$1,394.00	1	$1,394.00	EnviroTech
55 gallon drum reconditioned (clsed)	ea	$25.00	26	$650.00	Environmental Well
Explosion-proof regenerative blower	ea	$1,019.15			Isaacs
Blower inlet filter with filter cover	ea	$115.00			Grainger
Electrical parts/set-up	total	$200.00			Estimate
PVC 2 in to 1-1/2 in reducing bushing	ea	$4.98			U.S. Plastics
PVC 1-1/2 in cap sch 80	ea	$7.71			U.S. Plastics
PVC 1-1/2 in 90 deg elbow sch 80	ea	$2.62			U.S. Plastics
PVC 1-1/2 in sch 80 pipe	100 ft	$160.29			U.S. Plastics
Magnehelic gauge 0 - 10 in H_2O	ea	$47.00	1	$47.00	Dwyer
Magnahelic gauge 0 - 100 in H_2O	ea	$49.00	1	$49.00	Dwyer
Bentonite chips (assumed 0.75 ft^3)	bag	$10.16	44	$447.04	Unitek
Plastic cable ties 8 in long	100/bag	$6.00	1	$6.00	Instrmnt Lab Estimt
PVC 2 in male/female pts/plugs	ea	$3.85	4	$15.40	Boundary Waters
PVC 2 in sch 40 screen 5 ft	ea	$12.25			Boundary Waters
PVC 2 in sch 40 screen 10 ft	ea	$17.90	4	$71.60	Boundary Waters
PVC 4 in sch 40 screen 5 ft	ea	$26.00			Boundary Waters
PVC 4 in sch 40 screen 10 ft	ea	$43.00			Boundary Waters
PVC 2 in sch 40 casing 5 ft	ea	$7.75			Boundary Waters
PVC 2 in sch 40 casing 10 ft	ea	$19.00	3	$57.00	Boundary Waters
PVC 4 in sch 40 casing 5 ft	ea	$12.50			Boundary Waters
PVC 4 in sch 40 casing 10 ft	ea	$31.50			Boundary Waters
Ball valve, 2 in	ea	$20.74	2	$41.48	Pipe Valves

Ball valve, 4 in	ea	$163.81			Pipe Valves
Quickcrete ready mix, 80 b bags	ea	$3.69	4	$14.76	Columbus Hardware
Silica sand, 1 ft^3/bag	bag	$11.86	74	$877.64	Unitek
Std brass valve tags 1.5 in natural	ea (1-99)	$1.30	15	$19.50	Seton
Al flush mount well cover (8 in solid)	ea	$98.42	4	$393.68	Global Drilling
Mini male thermocouple plug	ea	$3.18	2	$6.36	Instrmnt Lab Estimt
Thermocouple wire (type K) 125 ft	roll	$62.83	1	$62.83	L.H. Marshall
MPT male connector 3/8 in X 1/4 in tube	ea	$1.31	11	$14.41	NewAge Industries
Nylon tubing 1/4 in	50 ft pk	$19.25	9	$173.25	Cole-Parmer
Plastic cable ties 8 in long	100/bag	$6.00	1	$6.00	Instrmnt Lab Estimt
Qck cnct F X 1/4 in tube 4Z-Q4CN-BBP	ea	$12.10	11	$133.10	Forberg Scientific
Qck cnct protector CP-Q4C-BB	ea	$5.01	11	$55.11	Forberg Scientific
Std brass valve tags 1.5 in natural	ea	$1.30	11	$14.30	Seton
Suction strainer (monitoring pt) 3/4 in	ea	$6.72	11	$73.92	Grainger
Gravel for suction screen 50 lbs	bag	$20.00	1	$20.00	Estimate
Vapor samples1L SUMMA, TPH/BTEX	ea	$130.00	7	$910.00	Air Toxics LTD.
Misc. Safety	set	$500.00	1	$500.00	Estimate
Travel (2 people)	rnd trip	$2,000.00			Estimate
Van rental	week	$250.00	2	$500.00	Estimate
per diem (2 people)	day	$200.00			Estimate
per diem (1 per)	day	$200.00	2	$400.00	
labor (2 people)	hr	$120.00			Estimate
labor (1 geo)	hr	$60.00	32	$1,920.00	Estimate
shipping	ea	$50.00	5	$250.00	Estimate
Installation Total				$18,291.38	

Comments:

Assumed 3 soil gas monitoring point wells and 1 vent well (1 VW and 1 VMP are also used for full-scale system)

Blower purchased in BLOWER section

Soil Analysis:

Item	*Unit*	*Unit Cost*	*Number*	*Cost*	*Vendor/source*
Analysis - TPH and BTEX (soil)	ea	$75.00	17	$1,300.00	Alpha Analytical Inc.
Analysis - Bulk density (soil)	ea	$10.00	4	$40.00	Alpha Analytical Inc.
Analysis - Grain size (soil)	ea	$50.00	4	$200.00	Alpha Analytical Inc.
Analysis - Particle density (soil)	ea	$50.00	4	$200.00	Alpha Analytical Inc.
Analysis - Total porosity (soil)	ea	$7.00	4	$28.00	Alpha Analytical Inc.
Soil Analysis Total				$1,768.00	

Comments:

Helium Tracer Test:

Item	*Unit*	*Unit Cost*	*Number*	*Cost*	*Vendor/source*
Helium gas cylinder	ea	$100.00	2	$200.00	Liquid Carbonic
Regulator CGA 590	ea	$245.00	2	$490.00	Liquid Carbonic Ind.
Flow meter model VFB	ea	$28.90	2	$57.80	Dwyer
Male connector 4MSC4N-B	ea	$1.52	12	$18.24	Forberg Scientific
Nylon tubing 1/4 in (natural)	50 ft pk	$19.25	3	$57.75	Cole-Parmer
PVC pipe, 1 in	20 ft	$14.03	1	$14.03	U.S. Plastics
PVC end cap, 1 in	ea	$3.23	2	$6.46	U.S. Plastics
1/4 in tube x 1/4 in MPT connector	ea	$1.52	10	$15.20	Forberg
Labor	hr	$60.00	4	$240.00	
Helium Tracer Test Total				$1,099.48	

Comments:

Labor is low due to overlap with respiration test.

Permeability Test:

Item	*Unit*	*Unit Cost*	*Number*	*Cost*	*Vendor/source*
Magnehelic gauge 0-0.25 in H_2O	ea	$54.00			Dwyer
Magnehelic gauge 0-0.50 in H_2O	ea	$47.00			Dwyer
Magnehelic gauge 0-2.0 in H_2O	ea	$47.00			Dwyer
Magnehelic gauge 0-10 in H_2O	ea	$47.00			Dwyer
Stop watch	ea	$39.95			Cole-Parmer
Nylon tubing 1/4 in (natural)	50 ft pk	$19.25	1	$19.25	Cole-Parmer
Labor	hr	$60.00	48	$2,880.00	
Permeability Test Total				$2,899.25	

Comments:

Number of items required defaults to zero due to the items being accounted for in *instrumentation* .

Respiration Test:

Item	*Unit*	*Unit Cost*	*Number*	*Cost*	*Vendor/source*
Latex tubing 3/16 in I.D.	100 ft	$52.58	1	$52.58	NewAge Industries
Tedlar bags	10/box	$82.00	4	$328.00	SKC
GasTech 3250X CO_2/O_2	ea	$3,700.00			Control Analytics
GasTech GT105 O_2/TPH	ea	$1,548.75			Control Analytics
Carbon dioxide, size s3 10% bal N_2	ea	$124.00	4	$496.00	Scott Specialty Gases
Hexane, size s3 4800 in air	ea	$124.00	4	$496.00	Scott Specialty Gases
Oxygen, size s3 10% balance N_2	ea	$124.00	4	$496.00	Scott Specialty Gases
Thermocouple readout (Fluke 52)	ea	$199.00			Grainger
Labor	hr	$45.00	60	$2,700.00	
Respiration Test Total				$4,568.58	

Comments:

Assumed respiration tests will be performed on pilot scale system or manageable portion of system only.

TOTAL $28,626.69

Vent Well Installation

Site Name and Location: PFFA
Project Estimator: M. Phelps
Estimation Date: 1/19/99

Estimated Parameters:

Area to be Bioventled, Ac	2.6
Blower 2 HP, cfm	160
Radius of Influence, ft	110
Depth of Contamination, ft	60
Depth of Construction, ft	65
Number of Vent Wells, calculated	3
Number of Soil Gas MPs, calculated	3
Top of Screen (vent well), ft	25
Bottom of Screen (vent well), ft	65
Upper Screen Depth (SG MP), ft	25
Lower Screen Depth (SG MP), ft	55
Borehole Diameter (vent well), in	10
Borehole Diameter (SG MP well), in	8
Drill Rate, ft/hr	8
Soil Sample Spacing, 1/ft	15
Mob/Demob Distance, mi	200
Bulking Factor for Soil, unitless	1.3
Heterogeneity Factor (samples/well)	1
Screen Diameter, in	4
Screen Length, ft, calculated	40
SG MP Screen Interval, ft	15
Bentonite Plug Thickness, ft	5
VW Installation Total Cost	**$13,011**

User Option:

3-1/4 in Environ. soil sampling kit	☑
PVC 2 in sch 40 screen 5 ft	☐
PVC 2 in sch 40 screen 10 ft	☑
PVC 4 in sch 40 screen 5 ft	☐
PVC 4 in sch 40 screen 10 ft	☐
PVC 2 in sch 40 casing 5 ft	☐
PVC 2 in sch 40 casing 10 ft	☑
PVC 4 in sch 40 casing 5 ft	☐
PVC 4 in sch 40 casing 10 ft	☐

Vent Well Installation Item & Cost:

Item	*Unit*	*Unit Cost*	*Number*	*Cost*	*Vendor/source*
Driller Mob/Demob of equipment	mile	$3.00	400	$1,200.00	Gregg Drilling
Driller travel	crew hr	$60.00			Layne Env Services
Driller Per diem, per crew	crew day	$168.00	3	$504.00	Gregg Drilling
Driller charge rate, (labor & equip)	hour	$210.00			Layne Env Services
Driller charge rate (labor & equip)	foot	$25.00	130	$3,250.00	Gregg Drilling
3-1/4 in Environmental soil sampling kit	ea	$1,394.00	1	$1,394.00	EnviroTech
55 gallon drum reconditioned (clsed)	ea	$25.00	19	$475.00	Environmental Well
Misc. Safety	set	$500.00	1	$500.00	Estimate
Travel (2 people)	rnd trip	$2,000.00			Estimate
Van rental	week	$250.00	1	$250.00	Estimate
per diem (1 per)	day	$100.00	3	$300.00	Estimate
labor (1 geo)	hr	$60.00	30	$1,800.00	Estimate
shipping	ea	$50.00	13	$650.00	Estimate
Analysis - TPH and BTEX (soil)	ea	$75.00	9	$650.00	Alpha Analytical Inc.
Analysis - Bulk density (soil)	ea	$10.00	4	$40.00	Alpha Analytical Inc.
Analysis - Grain size (soil)	ea	$50.00	4	$200.00	Alpha Analytical Inc.
Analysis - Particle density (soil)	ea	$50.00	4	$200.00	Alpha Analytical Inc.
Analysis - Total porosity (soil)	ea	$7.00	4	$28.00	Alpha Analytical Inc.
Bentonite chips, (assumed 0.75 ft^3)	bag	$10.16	46	$467.36	Unitek
Plastic cable ties 8 in long	100/bag	$6.00	1	$6.00	Instrmnt Lab Estimt
PVC 2 in male/female pts/plugs	ea	$3.85			Boundary Waters
PVC 2 in sch 40 screen 5 ft	ea	$12.25			Boundary Waters
PVC 2 in sch 40 screen 10 ft	ea	$17.90	12	$214.80	Boundary Waters
PVC 4 in sch 40 screen 5 ft	ea	$26.00			Boundary Waters
PVC 4 in sch 40 screen 10 ft	ea	$43.00			Boundary Waters
PVC 2 in sch 40 casing 5 ft	ea	$7.75			Boundary Waters
PVC 2 in sch 40 casing 10 ft	ea	$19.00	8	$152.00	Boundary Waters
PVC 4 in sch 40 casing 5 ft	ea	$12.50			Boundary Waters
PVC 4 in sch 40 casing 10 ft	ea	$31.50			Boundary Waters
Ball valve, 2 in	ea	$20.74	3	$62.22	Pipe Valves
Ball valve, 4 in	ea	$163.81			Pipe Valves
Quickcrete ready mix, 80 lb bags	ea	$3.69	3	$11.07	Columbus Hardware
Silica sand, ft^3/bag	bag	$11.86	55	$652.30	Unitek
Std brass valve tags 1 5 in natural	ea (1-99)	$1.30	3	$3.90	Seton
Total				$13,010.65	

Comments

Assumes one of the required VWs is already installed from the pilot test.

SG Monitoring Point Installation

Site Name and Location: PFFA
Project Estimator: M. Phelps
Estimation Date: 1/19/99

Estimated Parameters:

Area to be Biovented, Ac	2.6
Blower 2 HP, cfm	160
Radius of Influence, ft	110
Depth of Contamination, ft	60
Depth of Construction, ft	65
Number of Vent Wells, calculated	3
Number of Soil Gas MPs, calculated	3
Top of Screen (vent well), ft	25
Bottom of Screen (vent well), ft	65
Upper Screen Depth (SG MP), ft	25
Lower Screen Depth (SG MP), ft	55
Borehole Diameter (vent well), in	10
Borehole Diameter (SG MP well), in	8
Drill Rate, ft/hr	8
Soil Sample Spacing, 1/ft	15
Mob/Demob Distance, mi	200
Bulking Factor for Soil, unitless	1.3
Heterogeneity Factor (samples/well)	1
Screen Diameter, in	4
Screen Length, ft, calculated	40
SG MP Screen Interval, ft	15
Bentonite Plug Thickness, ft	5
SG MP Installation Total Cost	**$13,468**

User Option:

3-1/4 in Environ. soil sampling kit ☑

Soil Gas Monitoring Point Item & Cost:

Item	Unit	Unit Cost	Number	Cost	Vendor/source
Driller Per diem, per crew	crew day	$168.00	2	$336.00	Gregg Drilling
Driller charge rate (labor & equip)	hour	$210.00			Layne Env Services
Driller charge rate (labor & equip)	foot	$35.00	130	$4,550.00	Gregg Drilling
3-1/4 in Environmental soil sampling kit	ea	$1,394.00	1	$1,394.00	EnviroTech
55 gallon drum reconditioned (clsed)	ea	$25.00	13	$325.00	Environmental Wells
Analysis - TPH and BTEX (soil)	ea	$75.00	9	$650.00	Alpha Analytical Inc.
Analysis - Bulk density (soil)	ea	$10.00	4	$40.00	Alpha Analytical Inc.
Analysis - Grain size (soil)	ea	$50.00	4	$200.00	Alpha Analytical Inc.
Analysis - Particle density (soil)	ea	$50.00	4	$200.00	Alpha Analytical Inc.
Analysis - Total porosity (soil)	ea	$7.00	4	$28.00	Alpha Analytical Inc.
Misc. Safety	set	$500.00			Estimate
Travel (2 people)	rnd trip	$2,000.00			Estimate
Van rental	week	$250.00	1	$250.00	Estimate
per diem (1 geo)	day	$100.00	3	$300.00	Estimate
labor (1 geo)	hr	$60.00	25	$1,500.00	Estimate
shipping	ea	$50.00	13	$650.00	Estimate
Al flush mount well cover (8 in solid)	ea	$98.42	3	$295.26	Global Drilling
Bentonite chips (assumed 0.75 ft^3)	bag	$10.16	33	$335.28	Unitek
Quickcrete ready mix, 80 lb bags	ea	$3.69	3	$11.07	Columbus Hardware
Silica sand (assumed 3/4 ft^3)	bag	$11.86	45	$533.70	Unitek
Mini male thermocouple plug	ea	$3.18	2	$6.36	Instrmnt Lab Estimt
Thermocouple wire (type K) 125 ft	roll	$62.83	1	$62.83	L.H. Marshall
MPT male connector 3/8 in X 1/4 in tube	ea	$1.31	11	$14.41	NewAge Industries
Nylon tubing 1/4 in	50 ft pk	$19.25	9	$173.25	Cole-Parmer
Plastic cable ties 8 in long	100/bag	$6.00	7.8	$46.80	Instrmnt Lab Estimt
Qck cnct F X 1/4 in tube 4Z-Q4CN-BBP	ea	$12.10	11	$133.10	Forberg Scientific
Qck cnct protector CP-Q4C-BB	ea	$5.01	11	$55.11	Forberg Scientific
Std brass valve tags 1.5 in natural	ea	$1.30	11	$14.30	Seton
Suction strainer (monitoring pt) 3/4 in	ea	$6.72	11	$73.92	Grainger
Gravel for suction screen 50 lbs	bag	$20.00	1	$20.00	Estimate
Vapor samples1L SUMMA, TPH/BTEX	ea	$130.00	7	$910.00	Air Toxics LTD.
Labor (1 geo)	hr	$60.00	6	$360.00	
Total				$13,468.39	

Comments

Driller mobilization/demobilization is accounted for in the vent well installation assembly.
Travel costs are accounted for in the vent well installation assembly.
Assumes one of the required VMPs is installed during the pilot test.

Blower System Installation

Site Name and Location: PFFA
Project Estimator: M. Phelps
Estimation Date: 1/19/99

Estimated Parameters:

Area to be Biovented, Ac	2.6
Blower 2 HP, cfm	160
Radius of Influence, ft	110
Depth of Contamination, ft	60
Depth of Construction, ft	65
Number of Vent Wells, calculated	3
Number of Soil Gas MPs, calculated	3
Top of Screen (vent well), ft	25
Bottom of Screen (vent well), ft	65
Upper Screen Depth (SG MP), ft	25
Lower Screen Depth (SG MP), ft	55
Borehole Diameter (vent well), in	10
Borehole Diameter (SG MP well), in	8
Drill Rate, ft/hr	8
Soil Sample Spacing, 1/ft	15
Mob/Demob Distance, mi	200
Bulking Factor for Soil, unitless	1.3
Heterogeneity Factor (samples/well)	1
Screen Diameter, in	4
Screen Length, ft, calculated	40
SG MP Screen Interval, ft	15
Bentonite Plug Thickness, ft	5
Blower System Installation Total Cost	**$20,762**

User Options:

PVC 2 in 90 deg elbow sch 40	☑
PVC 2 in sch 40 pipe	☑
PVC 2 in coupler sch 40	☑
PVC 2 in sch 40 Tee	☑
PVC 4 in 90 deg elbow sch 40	☐
PVC 4 in sch 40 pipe	☐
PVC 4 in coupler sch 40	☐
PVC 4 in sch 40 Tee	☐
PVC 2 in 90 deg elbow sch 80	☐
PVC 2 in sch 80 pipe	☐
PVC 2 in coupler sch 80	☐
PVC 2 in sch 80 Tee	☐
PVC 4 in 90 deg elbow sch 80	☐
PVC 4 in sch 80 pipe	☐
PVC 4 in coupler sch 80	☐
PVC 4 in sch 80 Tee	☐
Trenching & Excavation	☑

Blower System Installation Item & Cost:

Item	*Unit*	*Unit Cost*	*Number*	*Cost*	*Vendor/source*
Explosion-proof regenerative blower	ea	$1,019.15	1	$1,019.15	Isaacs
Blower inlet filter with filter cover	ea	$115.00	1	$115.00	Grainger
Electrical parts/set-up	total	$3,000.00	1	$3,000.00	Atwater Electric
PVC 2 in to 1-1/2 in reducing bushing	ea	$4.98	1	$4.98	U.S. Plastics
PVC 1-1/2 in cap sch 80	ea	$7.71			U.S. Plastics
PVC 1-1/2 in 90 deg elbow sch 80	ea	$2.62	1	$2.62	U.S. Plastics
PVC 1-1/2 in sch 80 pipe	100 ft	$160.29	0.02	$3.21	U.S. Plastics
Magnehelic gauge 0 - 10 in H_2O	ea	$47.00	1	$47.00	Dwyer
Magnahelic gauge 0 - 100 in H_2O	ea	$49.00	1	$49.00	Dwyer
Anemometer, hot wire	ea	$795.00	1	$795.00	TSI Inc
PVC cement	quart	$12.32	5.2	$64.06	U.S. Plastics
PVC primer	quart	$9.56	5.2	$49.71	U.S. Plastics
PVC 2 in end cap sch 40	ea	$0.82			U.S. Plastics
PVC 2 in 90 deg elbow sch 40	ea	$1.21	15.6	$18.88	U.S. Plastics
PVC 2 in sch 40 pipe	20 ft	$23.48	42.5	$997.90	U.S. Plastics
PVC 2 in coupling sch 40	ea	$0.73	42.5	$31.03	U.S. Plastics
PVC 2 in sch 40 Tee	ea	$1.49	3	$4.47	U.S. Plastics
PVC 4 in end cap sch 40	ea	$6.54			U.S. Plastics
PVC 4 in 90 deg elbow sch 40	ea	$7.85			U.S. Plastics
PVC 4 in sch 40 pipe	20 ft	$69.00			U.S. Plastics
PVC 4 in coupler sch 40	ea	$3.60			U.S. Plastics
PVC 4 in sch 40 Tee	ea	$11.65			U.S. Plastics
PVC 2 in end cap sch 80	ea	$7.71			U.S. Plastics
PVC 2 in 90 deg elbow sch 80	ea	$2.62			U.S. Plastics
PVC 2 in sch 80 pipe	20 ft	$32.00			U.S. Plastics
PVC 2 in coupler sch 80	ea	$3.25			U.S. Plastics
PVC 2 in sch 80 Tee	ea	$9.30			U.S. Plastics
PVC 4 in end cap sch 80	ea	$31.09			U.S. Plastics
PVC 4 in 90 deg elbow sch 80	ea	$10.46			U.S. Plastics
PVC 4 in sch 80 pipe	20 ft	$95.68			U.S. Plastics
PVC 4 in coupler sch 80	ea	$11.52			U.S. Plastics
PVC 4 in sch 80 Tee	ea	$14.65			U.S. Plastics
Trenching Costs	ft	$16.00	850	$13,600.00	Marcor
Labor	hr	$60.00	16	$960.00	
Total				$20,762.00	

Comments

Assumed manifold to be 3 rows of 5 vent wells each.
For Pilot test, only one (1) vent well will be installed and operated, however, the cost for full system manifold construction are included. One blower was purchased for pilot test; only use this blower cost to scale up to full site size.
Number of blowers required based on replacement of soil void volume every 1 day, assuming porosity of 0.3, and blower flowrate into soil is 0.25 of blower capacity.

Operation and Maintenance

Site Name and Location: PFFA
Project Estimator: M. Phelps
Estimation Date: 1/19/99

Estimated Parameters:

Area to be Biovented, Ac	2.6
Blower 2 HP, cfm	160
Radius of Influence, ft	110
Depth of Contamination, ft	60
Depth of Construction, ft	65
Number of Vent Wells, calculated	3
Number of Soil Gas MPs, calculated	3
Top of Screen (vent well), ft	25
Bottom of Screen (vent well), ft	65
Upper Screen Depth (SG MP), ft	25
Lower Screen Depth (SG MP), ft	55
Borehole Diameter (vent well), in	10
Borehole Diameter (SG MP well), in	8
Drill Rate, ft/hr	8
Soil Sample Spacing, 1/ft	15
Mob/Demob Distance, mi	200
Bulking Factor for Soil, unitless	1.3
Heterogeneity Factor (samples/well)	1
Screen Diameter, in	4
Screen Length, ft, calculated	40
SG MP Screen Interval, ft	15
Bentonite Plug Thickness, ft	5
O&M Total Cost	**$11,113**

Operation & Maintenance Item & Cost:

Item	*Unit*	*Unit Cost*	*Number*	*Cost*	*Vendor/source*
Filter cover replacement	ea	$13.75	6	$82.50	Grainger
Carbon dioxide, size s3 10% bal N_2	ea	$124.00	4	$496.00	Scott Specialty Gases
Hexane, size s3 4800 in air	ea	$124.00	4	$496.00	Scott Specialty Gases
Oxygen, size s3 10% balance N_2	ea	$124.00	4	$496.00	Scott Specialty Gases
Tedlar bags	10/box	$82.00	6	$492.00	SKC
Std brass valve tags 1.5 in natural	ea	$1.30	14	$18.20	Seton
Miscellaneous replacement parts	ea	$1,000.00	1	$1,000.00	
Power	kwh	$0.11	45,745	$5,031.92	
Labor	hr	$60.00	50	$3,000.00	
Total				$11,112.62	

Comments:

Appendix H
Sample Calculation for Radius of Influence Estimate

A method for estimating the required air flow rate to meet the maximum demand of the microorganisms is provided in Section 2.2 of Volume II of the USEPA bioventing protocol (USEPA ORD, 1995):

$$Q = \frac{k_o \bullet V \bullet \theta_a}{(C_{max} - C_{min})} \qquad \text{(H-1)}$$

where:

Q	=	volumetric air flow rate [cubic feet per day (cfd)]
k_o	=	oxygen-utilization rate (*in situ* respiration rate) [%/day]
V	=	volume of contaminated soil [cubic feet]
θ_a	=	air-filled porosity [volume air/volume soil]
C_{max}	=	oxygen concentration of background/injected air [%] (typically 20.9%)
C_{min}	=	minimum oxygen concentration for aerobic conditions [%] (typically 5.0%)

Assuming that the volume of contaminated soil which is being treated by air injection is cylindrical (resulting from air injection at one central vent well):

$$V = \pi \bullet R_i^{\,2} \bullet h \qquad \text{(H-2)}$$

where:

V	=	volume of treated soil [cubic feet]
R_i	=	radius of influence [feet]
h	=	thickness of treated soil [feet] (typically screened interval or total thickness of permeable soil through which air flows)

Equation (H-1) can be rearranged and combined with Equation (H-2) to solve for the radius of influence, R_i, which can be achieved at a given air flow rate, Q:

$$R_i = \sqrt{\frac{Q \bullet (C_{max} - C_{min})}{\pi \bullet h \bullet k_o \bullet \theta_a}} \qquad \text{(H-3)}$$

Using the data from Test 4 presented in Table 6:

Q	=	175,000 cf/52 days = 3,365 cfd	h	=	35 feet
C_{max}	=	20.9 %	k_o	=	1.0 %/day
C_{min}	=	5.0 %	θ_a	=	0.27

and substituting into Equation (H-3):

$$R_i = \sqrt{\frac{3365 \bullet (20.9 - 5.0)}{\pi \bullet 35 \bullet 1.0 \bullet 0.27}} \qquad = 42 \text{ feet.}$$